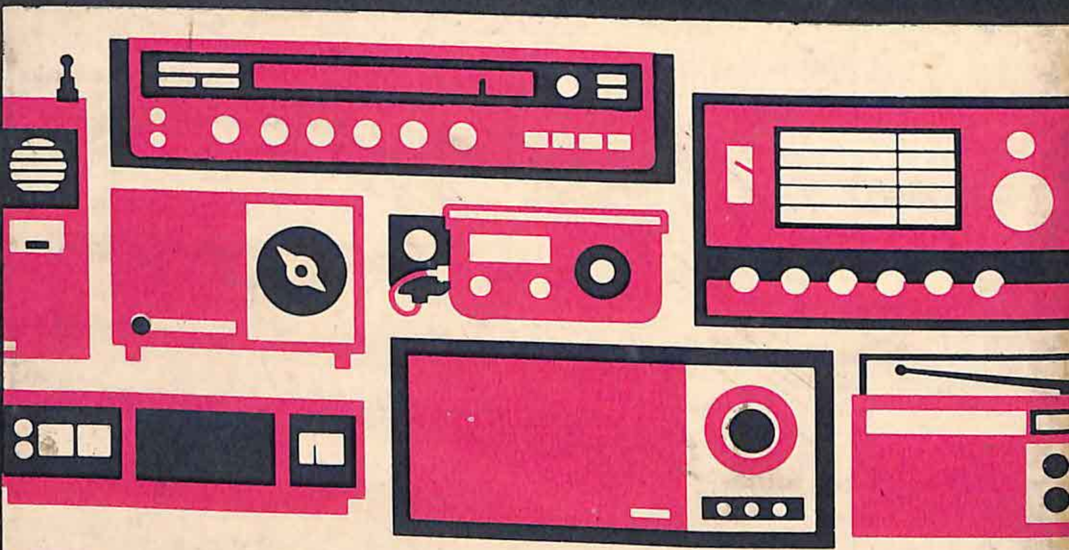
BASIC RADIO

REVISED EDITION

VOLUME 1



MARVIN TEPPER

DC ELECTRICITY

ELECTRONS AND PROTONS
ELECTROSTATICS
CURRENT

POWER
DC CIRCUITS
MAGNETISM

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BASIC RADIO

vol. 1

REVISED EDITION

MARVIN TEPPER

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PREFACE

Basic Radio is a course in communications electronics, as distinct from a general course in electronics. The text deals with the circuitry and techniques used for the transmission and reception of intelligence via radio energy. Assuming no prior knowledge of electricity or electronics, the six volumes of this course "begin at the beginning" and carry the reader in logical steps through the study of electricity and electronics required for a clear understanding of radio receivers and transmitters. Illustrations are used profusely to reinforce the highlights of the text. All examples given are based on actual or typical circuitry to make the course as practical and realistic as possible. Most important, the text provides a solid foundation upon which the reader can build his further, more advanced knowledge.

No prior knowledge of electricity or electronics is required for the understanding of this series. Because this series embraces a vast amount of information, it cannot be read like a novel, skimming through for the high points. Each topic contains a carefully selected thought or group of thoughts, so that each unit can be studied as a separate subject. Mathematics is kept to a minimum and, where necessary, the mathematical methods are fully explained.

This Revised Edition of *Basic Radio* retains the structure of the First Edition. Volume 1 treats d-c electricity. The slightly more involved subject of a-c electricity is presented in Volume 2. Equipped with this information, the reader is ready to study the operation of electron tubes and electron tube circuits in Volume 3, including power supplies, amplifiers, oscillators, etc. The components of electronic circuitry presented in Volumes 1 through 3 are assembled in Volume 4, which discusses the complete radio receiver, AM and FM. Volume 5 gives special attention to the theory and circuitry of transistors and integrated circuits. Volume 6 covers the long-neglected subject of transmitters, antennas, and transmission lines. In sum, the full range of the fundamentals of communications electronics is covered in a manner that provides maximum comprehension with a minimum of effort.

To the many people whose thoughts and discussions have contributed to this series, my sincere appreciation. To my wife, Celia, and my daughters, Ruth and Shirley, with whom I would have preferred to spend more time, my heartfelt thanks and gratitude for their assistance and understanding patience.

MARVIN TEPPER

Falmouth, Massachusetts

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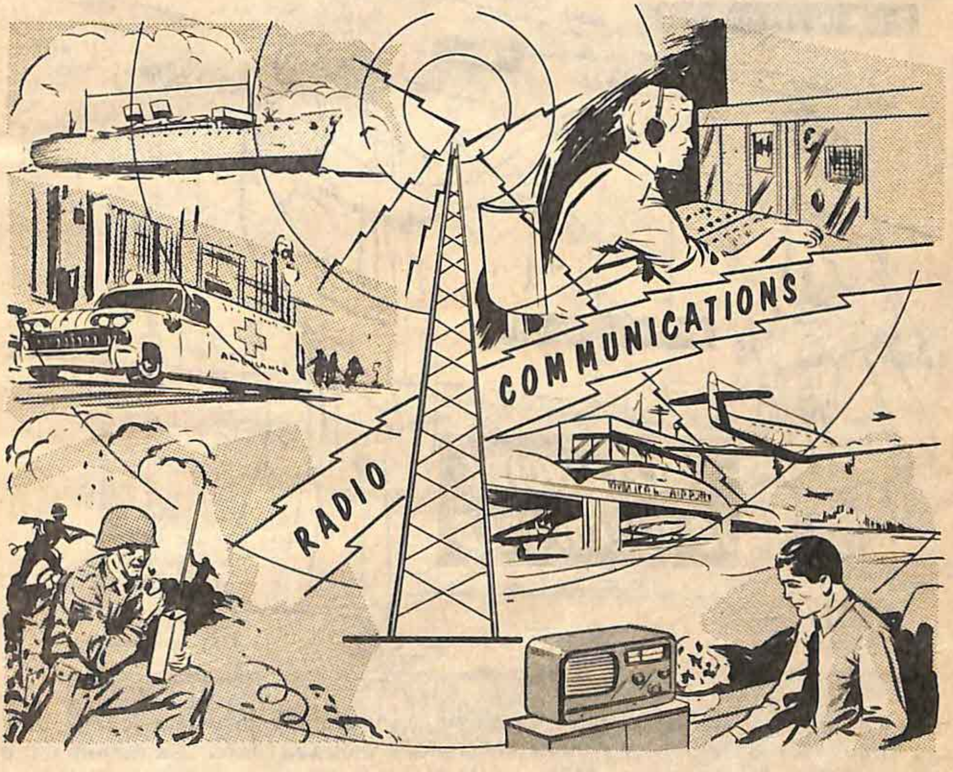
Introduction to Radio

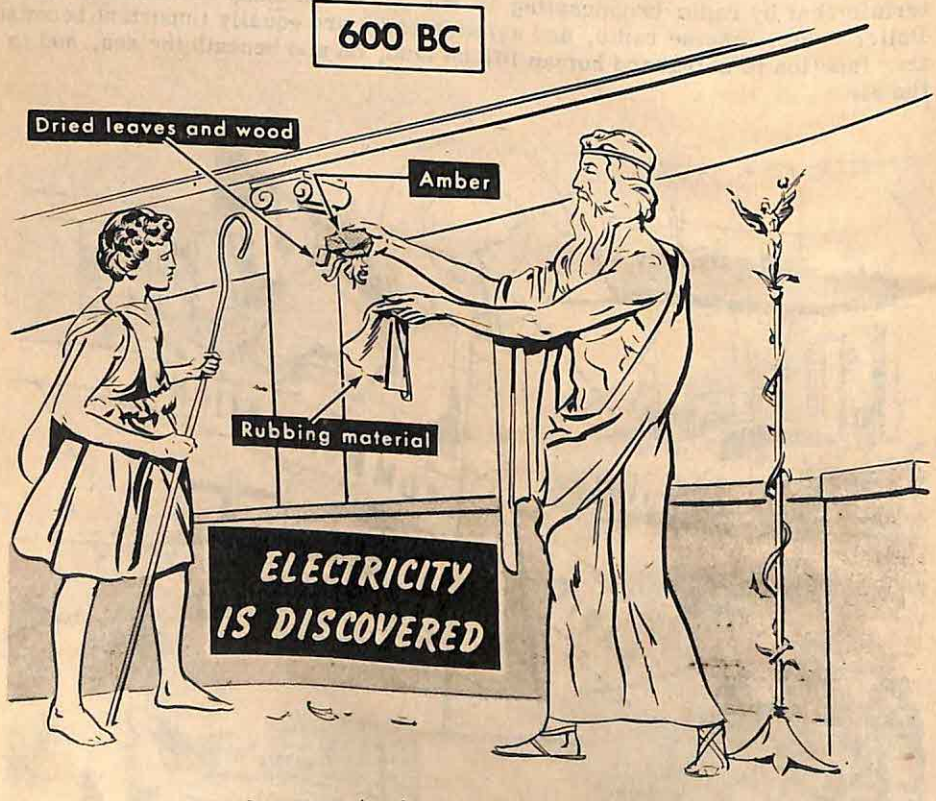
Radio is the name applied to the most successful and most frequently used facility for communicating with all parts of the world. Radio communication is speedy and reliable. An important news event -- a political incident, the death of a famous person, any significant occurrence anywhere in the world -- can be made known instantly everywhere else in the world through the medium of radio. The speed of the radio wave is approximately 186,000 miles per second, rapid enough to circle the globe at the equator slightly more than seven times per second. But the dissemination of news, culture and entertainment by radio broadcasting is but one of the many functions of radio. Police radio, marine radio, and aviation radio are equally important because they function to safeguard human life on land, on and beneath the sea, and in the air.



Without the benefits of radio, conquest of space would be impossible. The transmission of vital information from satellites to earth is one application of radio in this effort. Television is basically a radio system. The ability to detect an unseen hostile target and to locate its position and distance from a point of observation is another application of radio: it is called Radar -- RAdio Detection And Ranging. An understanding of the workings of radio is the basis for understanding the widespread applications of electronics. And it all begins with a study of electricity.

The Early History of Electricity

Knowledge concerning electricity started with the Greeks. It is said that at about 600 BC, the Greek philosopher Thales of Miletus discovered that a certain substance (now known as amber), when rubbed with certain materials, displayed a peculiar force. It would attract tiny bits of dried leaves and wood to itself. Thales had no explanation for the action, but he gave the name electron to the substance. The word "electron" is in use today but its meaning is far different now, as you will learn.

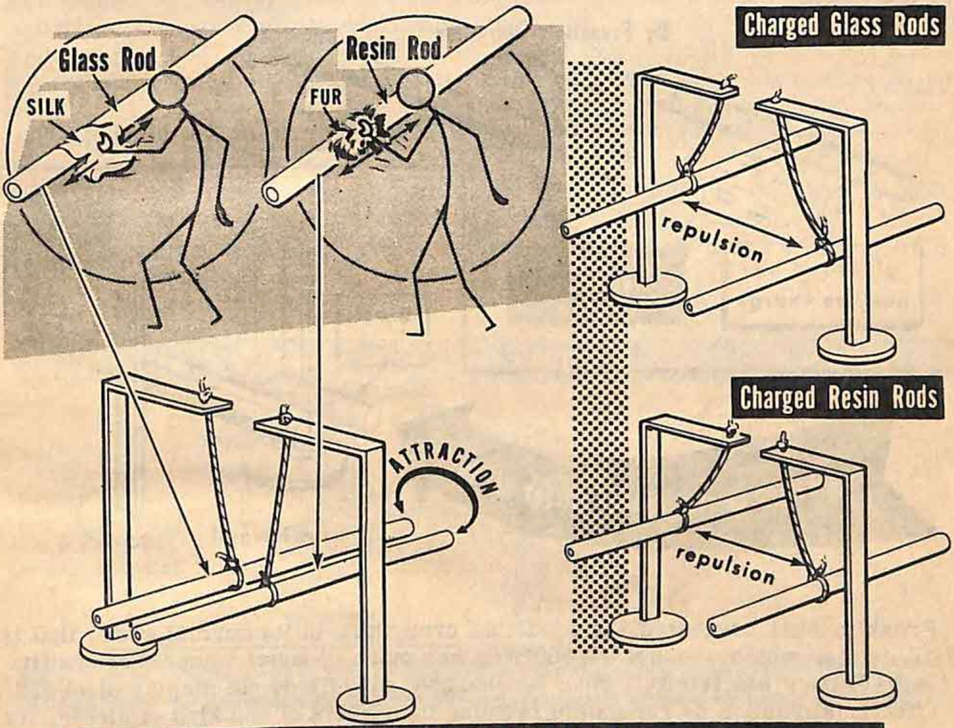


The behavior of amber remained a mystery for about a thousand years. But as time passed, more and more substances which behaved like amber were discovered. About the year 1600, an English scientist named William Gilbert compiled a list of so-called electriks, or substances that could be electrified or "charged with electricity," by rubbing (friction). When electrified, they could attract tiny objects such as bits of paper and threads of cloth. Then, in the early 18th century, experimenters with electriks discovered that many materials, when rubbed with other materials such as fur or wool, not only would attract tiny objects, but would attract or repel each other. The action was not understood and it was declared to be the display of electrical force due to a mysterious something known as electricity.

A Famous Experiment in Electricity

One of the far-reaching experiments performed in the field of electricity was the rubbing of a glass rod with a piece of silk, and the rubbing of a resin rod with a piece of fur, after which the two electrically charged or, simply, charged rods were suspended near each other and allowed to demonstrate their electrical effects on each other.

The charged resin rod and the charged glass rod attracted each other! The charged resin rod repelled another resin rod that had been similarly rubbed with the fur! The charged glass rod repelled another glass rod that had been rubbed with the silk!

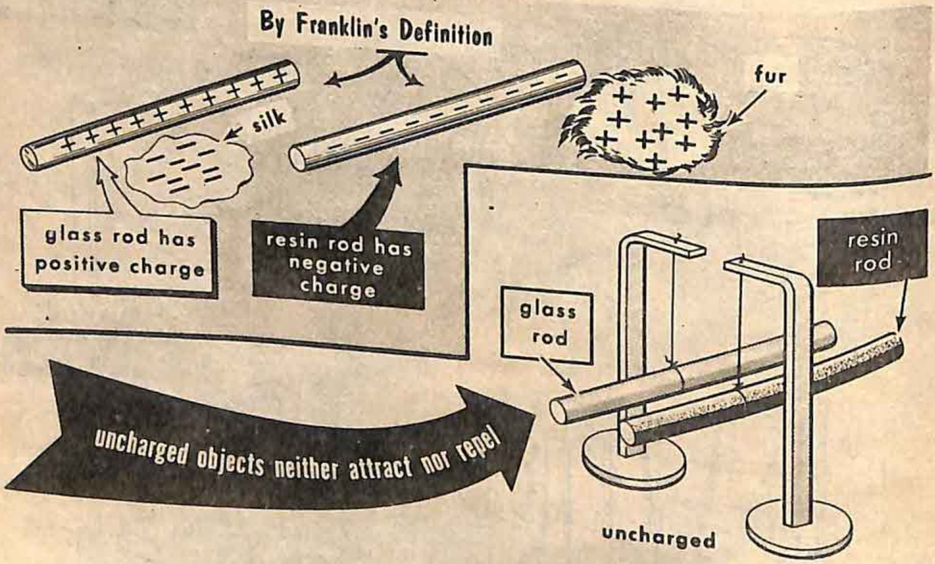


EARLY OBSERVATIONS MADE IN RUBBING GLASS AND RESIN RODS

It was also found that the action of rubbing the resin rod with the fur also had charged the fur. But the kind of charge was such that the fur and the resin rod were attracted to each other, whereas the charged glass rod and the fur repelled one another. The silk used for rubbing also displayed electrical effects. It too had acquired a charge when it was used to rub the glass rod, and its charge was such that it was attracted to the glass rod as well as by the fur, but it was repelled by the electrified resin rod.

A Famous Experiment in Electricity (Cont'd)

Many ideas were advanced as explanations for the actions observed. Charles Dufay, a French chemist, suggested that the different behavior of the charged rods was due to the presence of two kinds of electricity -- resinous in the resin rod, and vitreous in the glass. Benjamin Franklin, one of America's founders, recommended a change in the names identifying the two kinds of electricity. He suggested the name positive (symbolized by the plus sign +) for the kind of charge on the glass, and negative (symbolized by the minus sign -) for the kind of charge on the resin rod. These names were accepted and have been in use ever since.


By Franklin's Definition
silk
fur
glass rod has positive charge
resin rod has negative charge
uncharged objects neither attract nor repel
glass rod
resin rod
uncharged

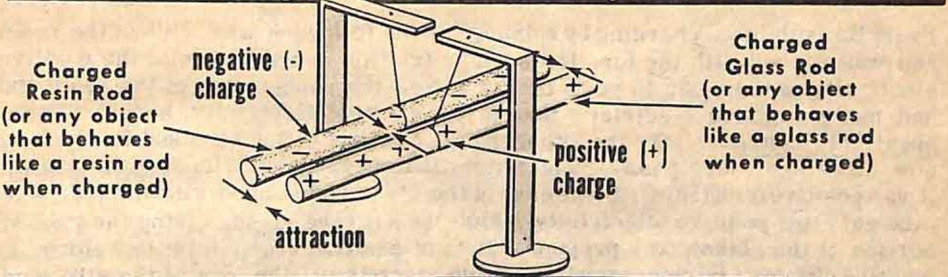
Franklin also suggested the idea that everything in its normal state, that is all objects which are not electrified, are made of equal amounts of positive and negative electricity. Such uncharged objects do not display electrical effects (attraction or repulsion) because the effects of one kind of electricity are offset by the effects of the other kind of electricity. He visualized the so-called electrified or charged condition of an object as being the presence of more of one kind of electricity than of the other kind. The part of the electrified resin rod which was rubbed was charged with negative electricity because it contained more negative electricity than positive electricity. The amount of negative charge was equal to the excess of negative electricity over positive electricity. In a practical sense, negative charge was produced in the resin rod by rubbing. The glass rod, on the other hand, was charged with positive electricity in the area where it was rubbed because it contained more positive electricity than negative electricity. The amount of positive charge was equal to the excess of positive electricity over negative electricity. Again, in a practical sense, positive charge was produced in the glass rod by rubbing.

A Famous Experiment in Electricity (Cont'd)

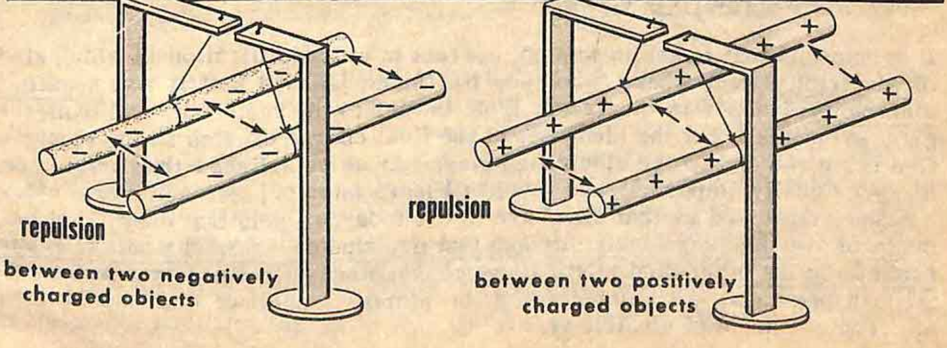
Franklin advanced several more fundamental ideas. He said that any object (body) which, when charged, behaved like the electrified resin rod, had a "negative charge." In other words, the glass rod was attracted to the resin rod and also the silk; therefore, the resin rod and the silk were charged with the same kind of electricity -- negative. By the same reasoning, any charged object (body) which behaved like the charged glass rod was charged with positive electricity. The resin rod was attracted to the glass rod and also to the fur; therefore, the glass rod and the fur were charged with the same kind of electricity -- positive.

It was observed that bodies which carried unlike charges -- the resin rod and the glass rod, the silk and the fur, the resin rod and the fur, the glass rod and the silk -- were attracted to each other. On the other hand, when the fur and the glass rod, or the resin rod and the silk (all of which carried the same kind of charge) were allowed to act on each other, it was noted that they repelled each other. From these findings came certain fundamental conclusions: namely, that bodies charged with unlike electricity attract each other, whereas bodies charged with the same kind of electricity repel each other. These experiments and observations did not explain what electricity was; they simply dealt with observable behavior of the assumed two kinds of electricity. Interestingly enough, these conclusions were correct and have become fundamental laws of electricity.

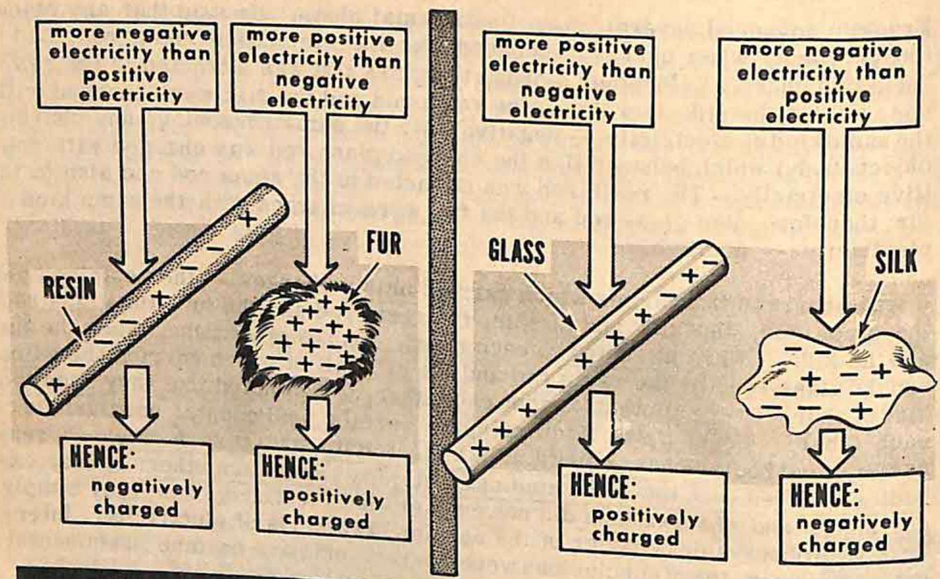
Bodies Charged With Unlike Electricity Attract Each Other



Bodies Charged With The Same Kind Of Electricity Repel Each Other



Electrical Charging by Rubbing


more negative electricity than positive electricity
more positive electricity than negative electricity
more positive electricity than negative electricity
more negative electricity than positive electricity
RESIN
FUR
GLASS
SILK
HENCE: negatively charged
HENCE: positively charged
HENCE: positively charged
HENCE: negatively charged

Early Explanation Of Negatively and Positively Charged Objects

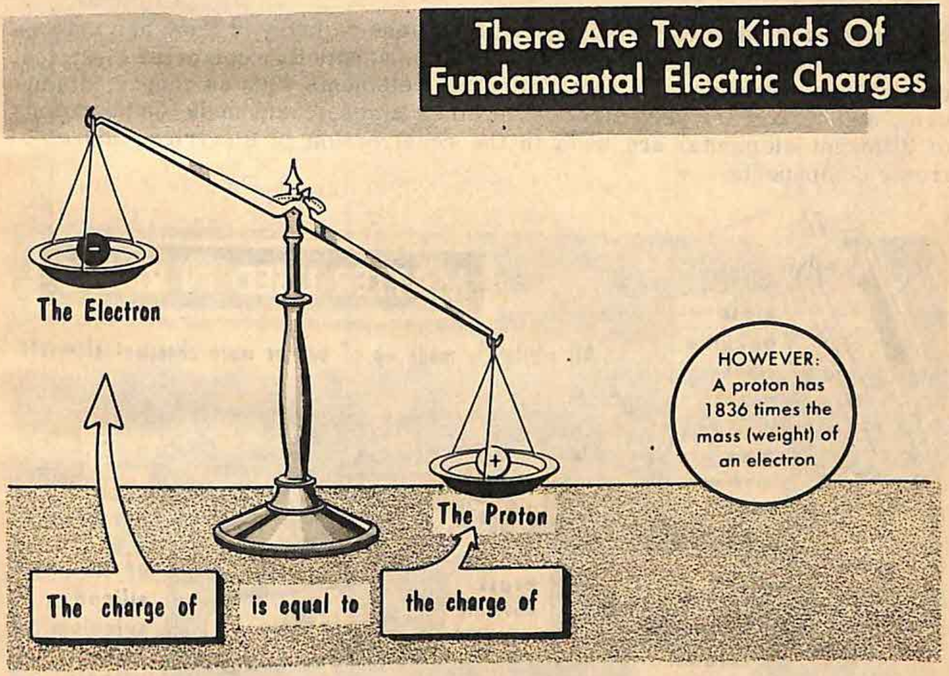
Franklin explained "charging by rubbing" in the following way. When the resin rod was rubbed with the fur, the surface friction caused some of the positive electricity in the resin to go to the fur. Now the rubbed part of the resin rod had more negative electricity than it had positive electricity; hence, it was negatively charged. On the other hand, the part of the fur used for rubbing now contained more positive electricity than negative electricity; therefore, it was positively charged. In the case of the glass rod rubbed with the silk, the silk gave up positive electricity which went to the glass, giving the rubbed portion of the glass rod a preponderance of positive electricity; therefore, a positive charge. Having given up positive electricity, the part of the silk used for rubbing was left with more negative electricity than positive electricity; hence, it was negatively charged.

It so happens that Franklin was not correct in his identification of which kind of electricity went where. Science has since learned that it was negative electricity which was displaced; from the fur to the resin rod, and from the glass to the silk. But the identities of the final charge created on the electrified resin rod and on the electrified glass rod as established then are in use today. Equally important, as you shall learn later on, is that several other concepts advanced at that time are in use today; namely that everything is made of two kinds of electricity and that one kind of electricity can be separated from the other kind. But before we can discuss the modern versions of these happenings, we must develop the atomic concept of matter and the electronic concept of electricity.

The Modern Concept of Electricity

Although our concepts of electricity differ substantially from the ideas of Franklin's time, the pattern of modern thinking, strangely enough, follows the explanation of electrical behavior as expressed then.

There are two kinds of electricity. Still using Franklin's terms, we speak of them as positive and negative. Whereas in Franklin's day electricity was visualized as a fluid, today we believe that electricity exists as minute, virtually weightless spherical specks or particles -- the positive electricity particles being called protons, and the negative electricity particles being called electrons. We don't know if the proton is, or just carries, a certain amount of positive electricity, or if the electron is, or just carries, a certain amount of negative electricity. Either concept is acceptable because it leads to the same thing.


There Are Two Kinds Of Fundamental Electric Charges
−
The Electron
+
The Proton
HOWEVER: A proton has 1836 times the mass (weight) of an electron
The charge of
is equal to
the charge of

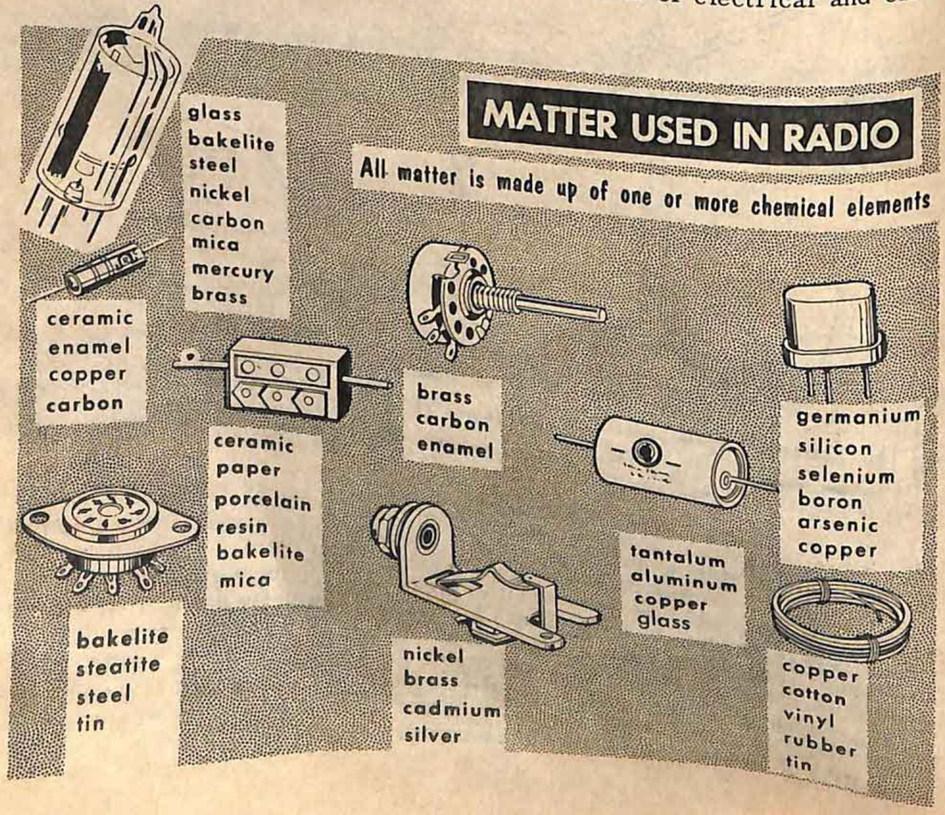
Man has never seen a proton or an electron because the particles are too tiny for even the greatest known magnification to make them visible. But this has not prevented the development of certain ideas about them. For instance, it has been established that the amount of positive electricity associated with a proton is exactly equal to the amount of negative electricity associated with an electron. Each is the smallest amount of electricity of its kind known. Therefore, the proton is the fundamental charge of positive electricity, and the electron is the fundamental charge of negative electricity. Each is an impractically small amount, but finite just the same. Operating electrical systems involve the motion of fantastic quantities of electrons, as you shall learn.

Matter and Chemical Elements

How do the specks of electricity -- protons and electrons -- fit into the scheme of things? The answer is that they are the main ingredients of everything.

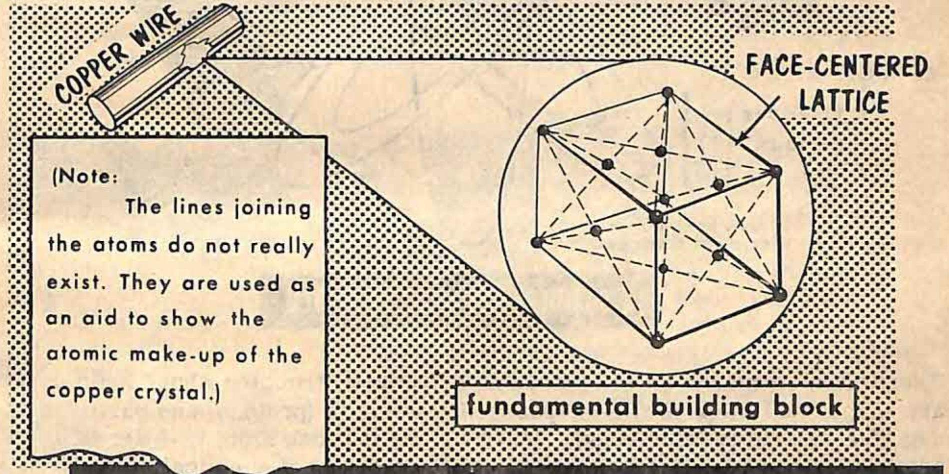
Everything in the world you can see or touch, and even the many things invisible to the naked eye but known to exist, make up the matter of the universe. Matter exists in solid, liquid, or gaseous states. Blood, skin, bone, steel, water, glass, rubber, powder, gold, smoke, copper, tobacco, and air are just some of the many examples of matter. Chemically speaking, all matter is made of one or more of the 103 "pure" substances identified as chemical elements. The word "pure" as applied to a chemical element is that it consists of only one substance. By definition, a chemical element is a substance which cannot be subdivided into two or more different substances by any known chemical means, nor can it be produced by the chemical combination of two or more different substances.

We are interested in chemical elements because so many of them are used as the ingredients that make up the various components that comprise electrical circuits and equipment. In some instances, elements such as copper, aluminum, and carbon are used directly; at other times, compounds (combinations of different elements) are used in the construction of electrical and electronic components.



The Atom

If a small quantity of a chemical element, solid, liquid or gas, could be reduced in amount by a continuous series of subdivisions, the fundamental building block of the element eventually would be reached. This is the atom. Science knows no way of performing such a subdivision, and consequently no one has ever seen an atom. But even though we lack this ability, we accept the idea that nature has built everything out of atoms. Atoms form the chemical elements, and chemical elements singly, or in combination make up everything else; therefore, in the fundamental sense, everything is made of atoms.

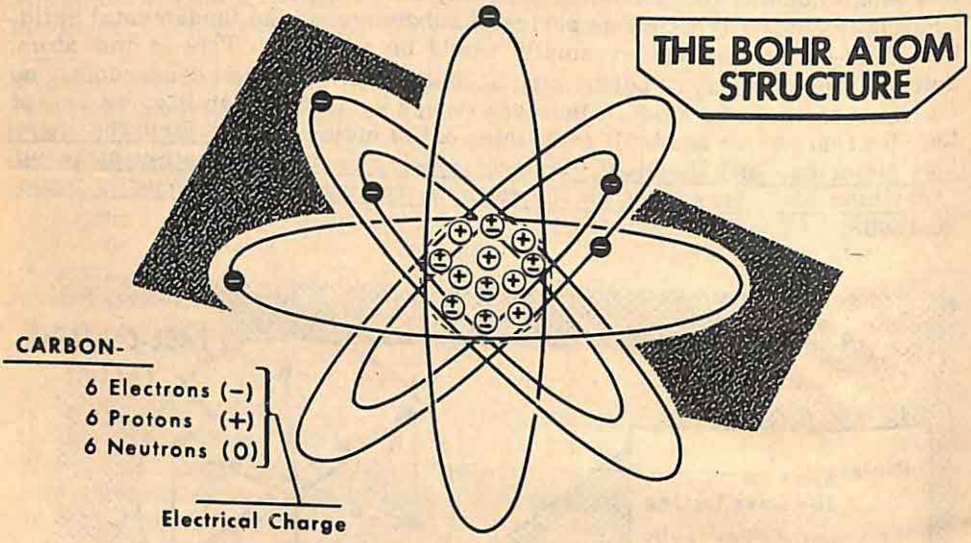


(Note: The lines joining the atoms do not really exist. They are used as an aid to show the atomic make-up of the copper crystal.)

THE COPPER CRYSTAL -- THE TINIEST PIECE OF COPPER THAT BEHAVES LIKE COPPER. IT CONSISTS OF 14 ATOMS IN A FIXED FORMATION.

The smallest possible amount of some gaseous elements which display the properties of the gases is a molecule, made up of two atoms that are in an electrical bond. Oxygen is one of these, Hydrogen and Chlorine are others. Then there are gaseous elements for which the smallest quantity of the substance is a single atom. Helium, Argon and Neon are examples. In the case of the elemental metals, a different situation prevails. The smallest amount of the element is a single atom, as for instance copper, silver, gold, iron, lead, tin and others, but the smallest amount of the metal which displays the physical properties of the metal -- expansion, contraction, malleability -- is a crystal. (Sometimes, the crystal of a metal is called a giant molecule). A crystal of a metal is an organization of atoms of the element arranged in a particular formation. For instance, the tiniest amount of pure copper which will behave like the metal is 14 atoms of copper arranged in a geometric pattern called a face-centered lattice. A length of copper wire would be made of a tremendous amount of these crystals. Other elemental metals have their atoms arranged in different formations. Remembering the geometric pattern of the crystal of copper is not vital to understanding the workings of electricity.

Every Atom Is Made of Electricity



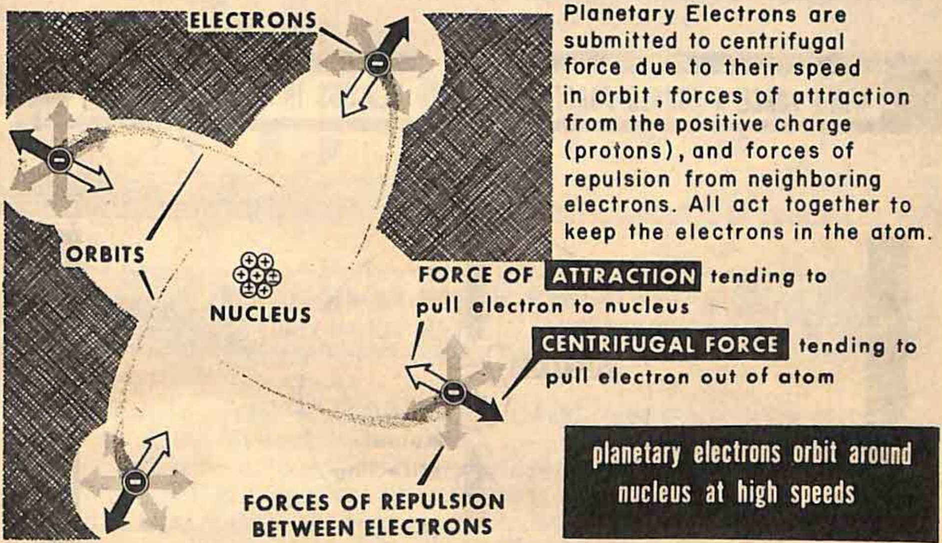
A SUBMICROSCOPIC SOLAR SYSTEM

Every atom (regardless of kind) is an organized structure whose main parts are comprised of particles of positive electricity (protons) and particles of negative electricity (electrons). When we say that one atom is different from another (each being representative of a different kind of chemical element), we mean simply that the two atoms are made of different amounts of positive electricity, with each having as much negative electricity as positive electricity.

A popular concept of the atom was advanced by Niels Bohr, a Danish physicist. He visualized the atom as having a stationary center (or nucleus) in which was concentrated all the positive electricity of the atom (all the protons). Also present in the nucleus of all but the Hydrogen atom was still another kind of particle called a neutron. Each kind of atom contained a different number of neutrons, but since the neutron contributes nothing of electrical character to the atom, we need not discuss it any further. Revolving around the nucleus with very high velocity and at different distances from it are the specks of negative electricity -- planetary electrons -- which balance the positive electricity content of the atom. In any one kind of atom, there are associated with it as many planetary electrons as there are protons in the nucleus, or as much negative electricity as positive electricity. As a convenience in identifying the different kinds of atoms, each kind is associated with a number and with one or two letters. The numerical reference states the number of protons in the atom (hence, the number of planetary electrons too), while the letter symbol identifies the chemical element. As typical examples, the Hydrogen atom (H) is #1; the Carbon atom (C) is #6; the Copper atom (Cu) is #29; the Silver atom (Ag) is #47, and so on.

Electrical Forces in the Atom

What keeps the circling electrons from flying out of the atom under the influence of the centrifugal force that each planetary electron feels? The general concept is that the electrons are held in their orbits against the pull of centrifugal force by the electrical force of attraction between the protons in the nucleus and the orbiting electrons. The electrical force is manifested as a mechanical force; it pulls the electrons inwards towards the nucleus while the centrifugal force is pulling the electrons outward away from the center. The two forces are in exact balance; therefore, the electrons do not leave the atom nor do they "fall" into the nucleus. Each fundamental particle of electricity is inseparably endowed with the property of attracting an oppositely charged particle to itself, and repelling every similarly charged particle. The protons in the nucleus also feel a pull towards the electrons, but the much greater mass of the individual proton keeps it put where it is.


ELECTRONS
ORBITS
NUCLEUS
FORCE OF ATTRACTION tending to pull electron to nucleus
CENTRIFUGAL FORCE tending to pull electron out of atom
FORCES OF REPULSION BETWEEN ELECTRONS

Planetary Electrons are submitted to centrifugal force due to their speed in orbit, forces of attraction from the positive charge (protons), and forces of repulsion from neighboring electrons. All act together to keep the electrons in the atom.

planetary electrons orbit around nucleus at high speeds

A force of repulsion exists between each orbiting electron and acts in all directions, thus keeping the planetary electrons in their positions in the orbits. A similar force of repulsion exists between individual protons which are separated, but when they are as densely packed as they are in the nucleus, there is a "something" which accounts for their not flying apart.

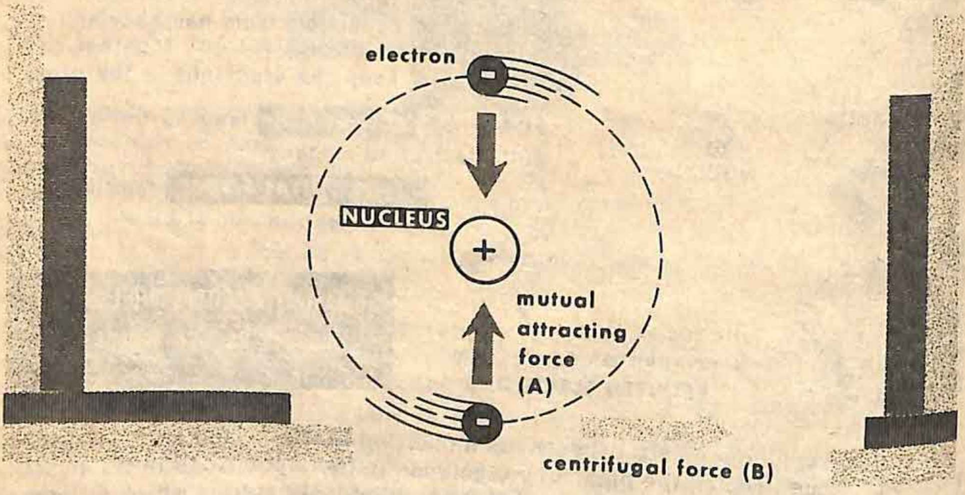
The electrical forces in the atom are fundamental and tremendous. Were this not so, the universe would fly apart. As long as the atom is in electrical equilibrium, that is, equal numbers of protons and electrons, the electrical and mechanical force condition is confined strictly to the inside of the atom. Neither the protons nor the electrons inside an electrically-neutral atom (equal numbers of protons and electrons) have any effect on other electrons and protons outside of the atom. This subject will receive more attention later, as we develop several related ideas.

Bound Electrons

The electrical forces referred to on the preceding page exist inside every atom but the behavior of these forces is not exactly the same in the different kinds of atoms. For our purposes, we need not consider the different kinds of atoms on an individual variety basis; it is sufficient if we deal with two main categories--nonmetals and metals. We shall consider each separately.

Under all normal conditions, the force of attraction between the protons in the nucleus and the planetary electrons in the atoms of nonmetals is sufficiently strong to keep all the electrons tightly "locked" inside the atomic structure. The electrons revolving in orbits close to the nucleus, as well as those revolving at the farthermost distances from the center of the atom, are "bound" to the atom. An occasional atom may let go of one of its outermost electrons, but by and large, we assume that the nonmetallic materials are made mainly of atoms which are in electrical balance (always have equal numbers of protons and electrons). They are electrically-neutral atoms.

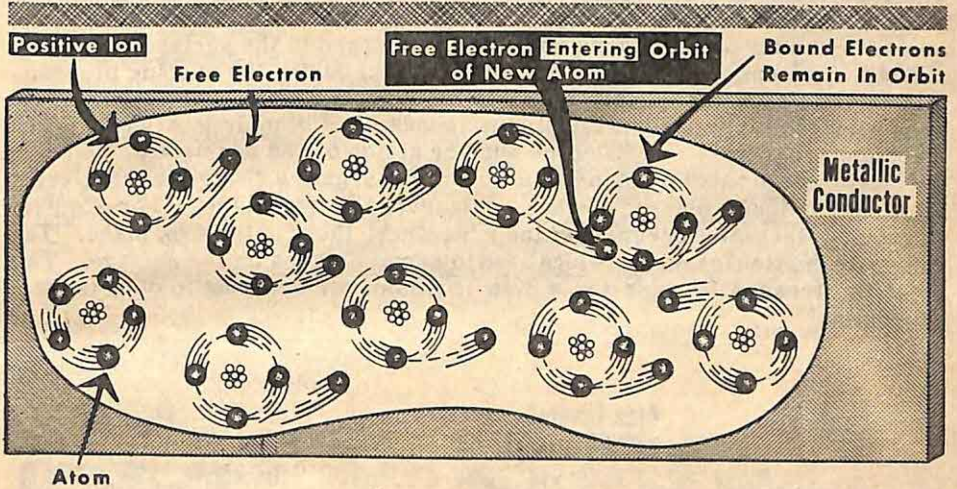
WHEN FORCE A EQUALS FORCE B, ELECTRON REMAINS IN ORBIT (IS BOUND)



This situation is not an unchangeable one. Given a different set of conditions (which we might call "abnormal") such as the application of a sufficiently strong external force--one strong enough to overcome the binding forces between the protons and outermost electrons inside the atomic structure--it is possible to upset the electrical balance. It is possible to literally "tear" one or more electrons out of the atom, or even temporarily "add" an electron to the atom. Strangely enough, such external forces can be developed rather easily. Rubbing the resin rod with the fur and the glass rod with the silk are examples of "abnormal" conditions--that is, the application of such external force. The surface atoms of the fur and the glass rod released electrons, whereas the surface atoms of the resin rod and the silk temporarily accepted them.

Free Electrons in Metals

We have explained how the electrons in the atoms of nonmetals are bound to the atom. On the other hand, it is an accepted theory that the protons in the nucleus of the atom of a metal hold onto all but one of the normal complement of planetary electrons.


Positive Ion
Free Electron
Free Electron Entering Orbit of New Atom
Bound Electrons Remain In Orbit
Metallic Conductor
Atom

FREE ELECTRONS MOVE IN RANDOM MOTION THROUGHOUT METALLIC CONDUCTOR

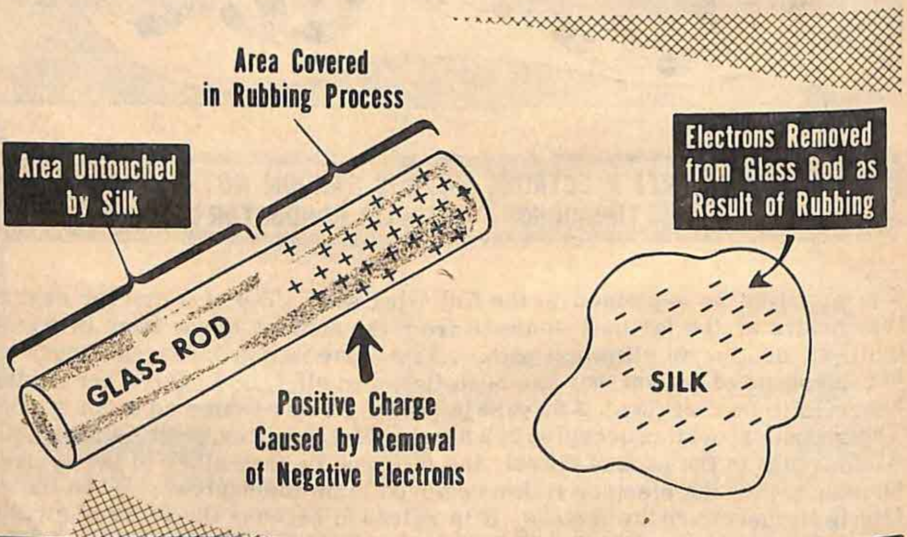
The situation is explained in the following way. The electron (or electrons) that orbits at the farthest distance from the nucleus in the atom of metals is believed to follow an elliptical path. (An ellipse is a geometrical figure which has the shape of a hoop that has been flattened slightly.) The other orbits are assumed to be circular. As a case in point, let us assume an atom of copper. The outermost orbit is occupied by a single electron, this orbit being elliptical. At one point in the path of travel, the electron is very close to the nucleus; at another point, the electron is far removed from the nucleus. When the electron is farthest from the nucleus, it is released because the force of attraction between it and the cluster of protons is not sufficiently strong to keep the electron in its orbit. It is believed that this action occurs in the atoms of all metals, although not exactly to the same extent in each kind.

The liberated electrons are called "free electrons." They wander among the atoms of the metal throughout all parts of the metal in a random manner (presumably uniformly distributed throughout the metal), as many moving in one direction as in another. Every atom which has lost an electron now has a preponderance of positive charge, that amounting to one proton. These atoms are called "positive ions." However, for every positive ion in the metal there is a free electron so that the balance between positive and negative electricity is maintained and the metal as a whole remains electrically neutral.

The Modern Concept of Charging

The modern concept of "charging with electricity" or simply, "charging," involves nothing more than disturbing either the equality of the electron and proton content in an object, or the uniform distribution of the negative and positive electricity content.

The four types of nonmetallic substances used in the Franklin experiment became charged because electrons were torn from the surface atoms of one material (the fur and the glass rod) and transferred to the surface atoms of the other material (the resin rod and the silk) during the rubbing process. The emphasis on the surface atoms is made for a reason. The atoms of all solid substances are to all intents and purposes fixed in their locations. When electrons are transferred from the surface atoms of one nonmetallic object to surface atoms of another nonmetallic object, the negative charge is transferred from one particular place to another. Whatever charge is given up or acquired by rubbing, the action occurs over the area where the friction took place. The charged condition is therefore localized to certain places on the surface. This point is stressed because the action is somewhat different in objects made of metals.


Area Covered in Rubbing Process
Area Untouched by Silk
Electrons Removed from Glass Rod as Result of Rubbing
GLASS ROD
SILK
Positive Charge Caused by Removal of Negative Electrons

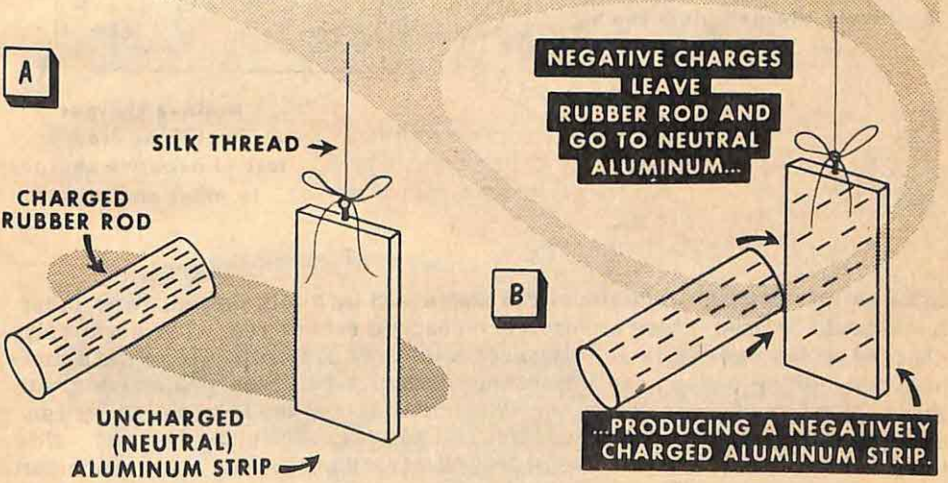
CHARGE ACQUIRED BY RUBBING OCCURS ONLY OVER AREA WHERE FRICTION TOOK PLACE

Charging by Contact

The frictional method of charging (rubbing) is applicable to nonmetals and metals alike, but not too successfully to the latter. A preferred method of charging metallic objects is by contact. We are concerned with the charging of metal objects because metals are used in radio equipment.

Let us assume we have a hard rubber rod which has been given a negative charge by some means. (Hard rubber behaves like resin). We also have a small strip of aluminum which is electrically neutral. The strip is suspended by a silk thread. We now make momentary contact between the charged rubber rod and the metal strip. Some of the electrons leave the rubber and go to the aluminum. Having given up some of its electrons, the rubber now has less negative charge; but now, the metal strip also has a negative charge. The total of the acquired electrons, plus the free electrons, plus the bound electrons in the atom of the metal exceeds the total of the protons in the metal. Thus, the total negative electricity content exceeds the total positive electricity content; hence, the net negative charge. However, unlike the behavior of the nonmetallic object, the electrons passed on to the aluminum distribute themselves uniformly over the entire surface of the strip, after which (to all intents and purposes) they are at rest.

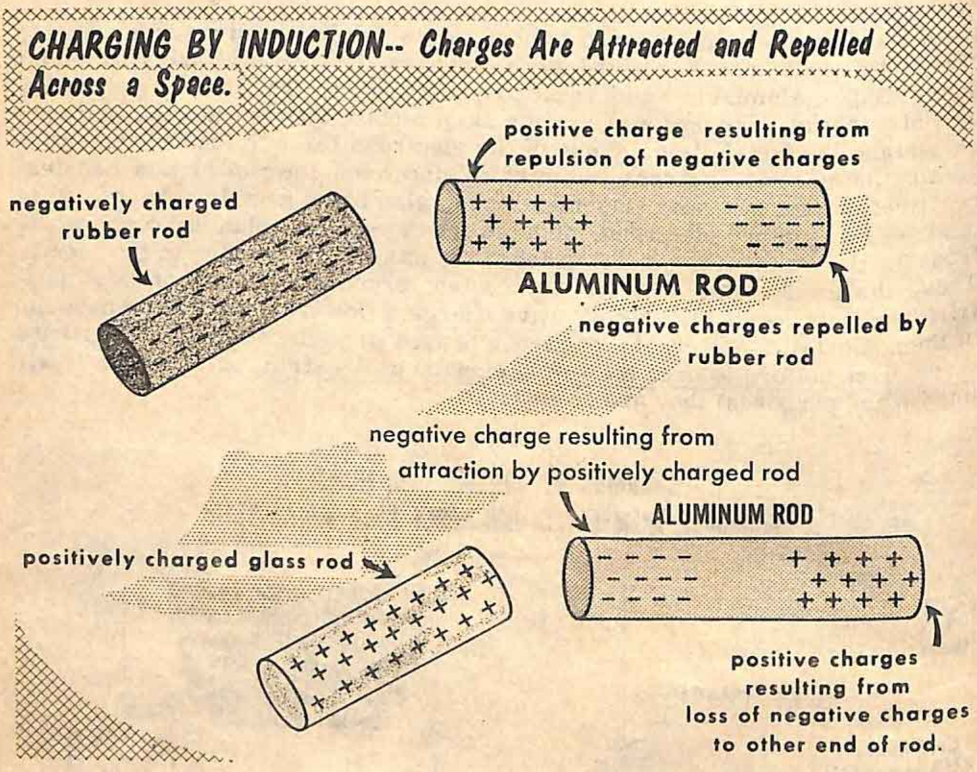
CHARGING BY CONTACT - CHARGES DISTRIBUTE THEMSELVES UNIFORMLY OVER METAL STRIP


A
SILK THREAD
CHARGED RUBBER ROD
UNCHARGED (NEUTRAL) ALUMINUM STRIP
NEGATIVE CHARGES LEAVE RUBBER ROD AND GO TO NEUTRAL ALUMINUM...
B
...PRODUCING A NEGATIVELY CHARGED ALUMINUM STRIP.

In other words, the acquired negative charge is not localized to the point of contact with the rubber. It exists everywhere on the aluminum surface. If a positively-charged glass rod had been used as the charging body in place of the negatively-charged rubber rod, some of the free electrons moving along the surface of the aluminum would have gone to the glass, leaving a preponderance of positively-charged atoms (positive ions) in the metal. The metal strip then would have been charged positively.

Charging by Induction

There is still another method of charging an object. It is called charging by induction. We shall apply it to metallic objects rather than nonmetallic because the practical applications of the phenomenon involve metallic components.



CHARGING BY INDUCTION-- Charges Are Attracted and Repelled Across a Space.

positive charge resulting from repulsion of negative charges
negatively charged rubber rod
ALUMINUM ROD
negative charges repelled by rubber rod
negative charge resulting from attraction by positively charged rod
ALUMINUM ROD
positively charged glass rod
positive charges resulting from loss of negative charges to other end of rod.

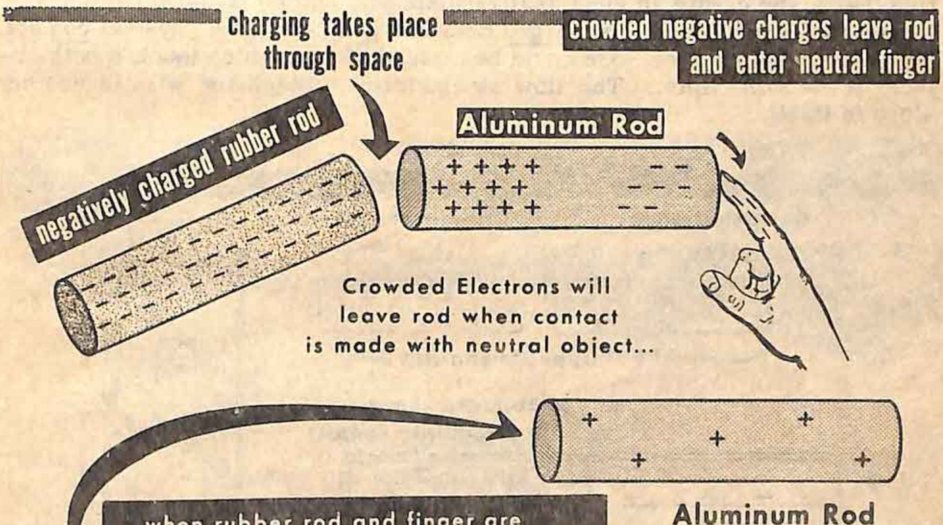
Imagine an uncharged aluminum rod suspended by a silk thread. (Any other metal could be used.) Also a negatively-charged rubber rod. The negatively-charged rubber rod exerts an influence on the free electrons within the aluminum rod, acting across the space separating the two rods. Complying with the law that like charges repel, the rubber rod drives the free electrons wandering in the aluminum rod away from the end nearest the rubber rod. Now there is a decrease in the number of free electrons at that end of the aluminum rod which is nearest the charged rubber rod and a crowding of free electrons at the other end of the metal rod. This condition exists as long as the charged rubber rod is held near the metal rod.

If, instead of using a negatively-charged rod as the charging body, we used a positively-charged glass rod, the free electrons in the metal rod would be attracted towards the end which is nearest the glass rod, causing a crowding at this end and a shortage at the other end.

Charging by Induction (Cont'd)

Let us continue the experiment with the metal bar being acted upon by the negatively-charged rubber rod. As shown in the illustration, some of the free electrons are crowded at the end away from the rubber, having been repelled from the end near the rubber rod by the energy associated with the negatively-charged rubber.

Now we momentarily touch the end of the metal rod farthest from the rubber. The human body is not the best-known path for electricity, but it is good enough for this purpose. The crowded electrons tending to repel each other readily leave the metal and go to the finger. Then, we remove the charged rubber rod from the vicinity of the metal rod. The free electrons inside the metal redistribute themselves uniformly throughout the metal, but now, there are more atoms shy electrons than there are free electrons in the metal. The metal rod contains more positive electricity than negative electricity; hence, it has acquired a positive charge. It is to be noted that a negatively-charged charging body induces a positive charge in the original electrical neutral body. In other words, the charge induced is the opposite of the inducing charge.

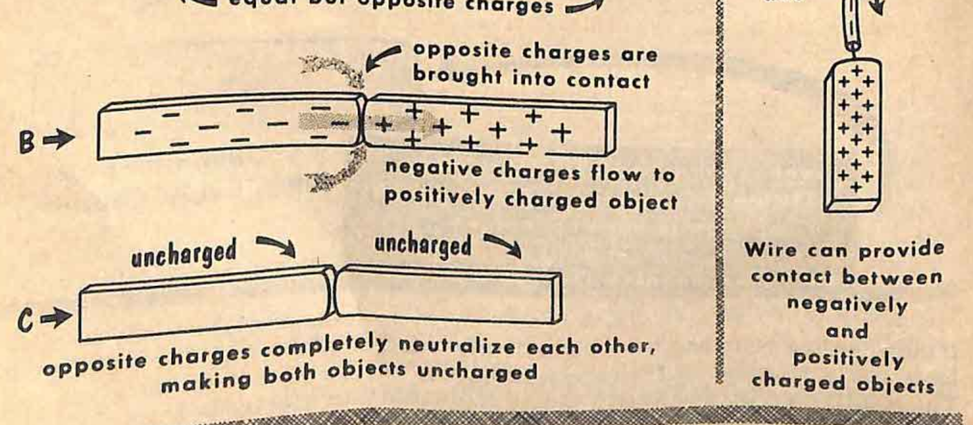

charging takes place through space
crowded negative charges leave rod and enter neutral finger
negatively charged rubber rod
Aluminum Rod
Crowded Electrons will leave rod when contact is made with neutral object...
...when rubber rod and finger are removed, remaining negative charges combine with positive charges. This results in a net positive charge, since some negative charges were lost.
Aluminum Rod (Positively Charged)

If the charging body had been a positively-charged glass rod, the metal would have had a shortage of free electrons at the end farthest from the glass rod. The positively-charged atoms at this end would pull electrons from the finger that touched the metal. Removing the charged glass rod from the vicinity of the metal would then leave the metal with more free electrons than positively-charged atoms -- or a net negative charge.

Discharging a Charged Object

You have learned that the electron and the proton are associated with electrical energy. If we think in terms of theory only, we say that a negative and positive charge are subject to a force which attracts each to the other; similar charges tend to repel each other. If we take the practical viewpoint, we realize that it is the electron, the very much lighter of the two fundamental charges of electricity, which performs the motion. (Each proton has about 1837 times the mass of an electron). Moreover, the positive electricity is locked inside the atom; it does not move under the influence of forces that act between charges. If we give a free electron the opportunity to move from one place to another under the influence of a nearby positive charge, it will do so, but the positive charge will not move.

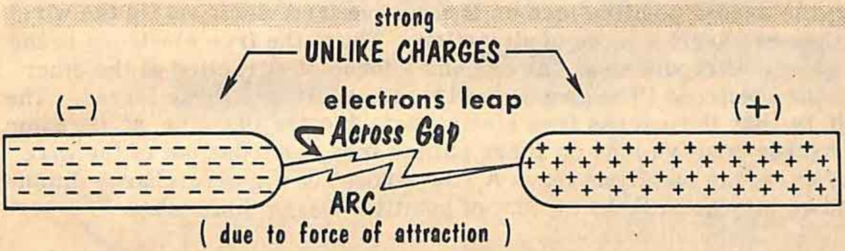
If we arrange for a negatively-charged object and a positively-charged one to make physical contact, the point of contact becomes the path over which the excess electrons on the negatively-charged object move to the positively-charged atoms on the positively-charged object. If both objects have equal amounts of unlike charge, all the electrons corresponding to the negative charge will flow to the positively-charged body, where they will neutralize the positive charge and create an electrically-balanced (neutral) condition in both objects. We have, in fact, discharged both charged objects by physical contact. Another kind of physical path could be a piece of wire which touches both objects at the same time. The flow of electrons through the wire is another story in itself.

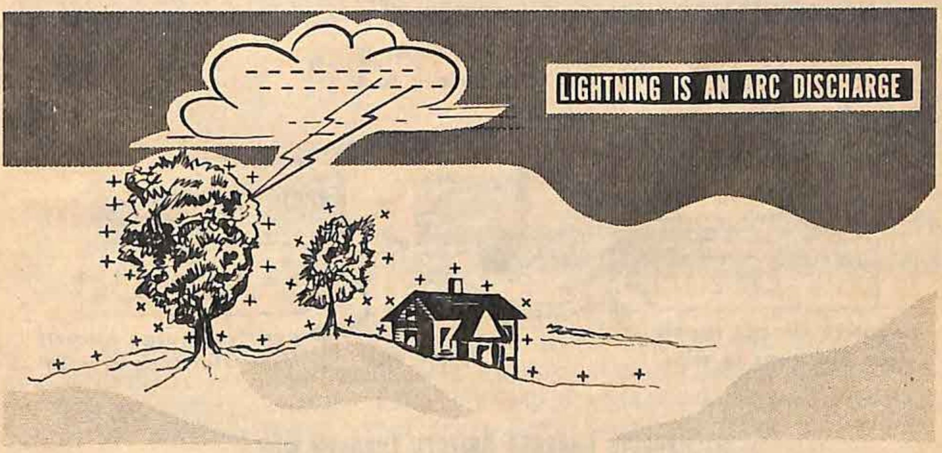

negatively charged object
positively charged object
A
equal but opposite charges
opposite charges are brought into contact
B
negative charges flow to positively charged object
uncharged
uncharged
C
opposite charges completely neutralize each other, making both objects uncharged
wire
Wire can provide contact between negatively and positively charged objects

CHARGED OBJECTS CAN BE DISCHARGED BY CONTACT

Discharging a Charged Object (Cont'd)

Objects bearing unlike charges can be discharged without using a physical path between them. Assume two objects, one with a very strong negative charge, the other with an equally strong positive charge. If the two charged objects are brought sufficiently close to each other but not touching, the excess electrons on the negative object will, under the influence of the force of attraction between unlike charges, leap across the gap to the positively-charged object. The movement of electrons through air produces a visible flash of light accompanied by an audible crackling sound. The visible phenomenon is called an arc. The greater the accumulation of the unlike charge on the two objects, the wider the separation that can be bridged by the arc. Lightning is an example of arc discharge between dissimilarly-charged clouds, or between a charged cloud and earth.



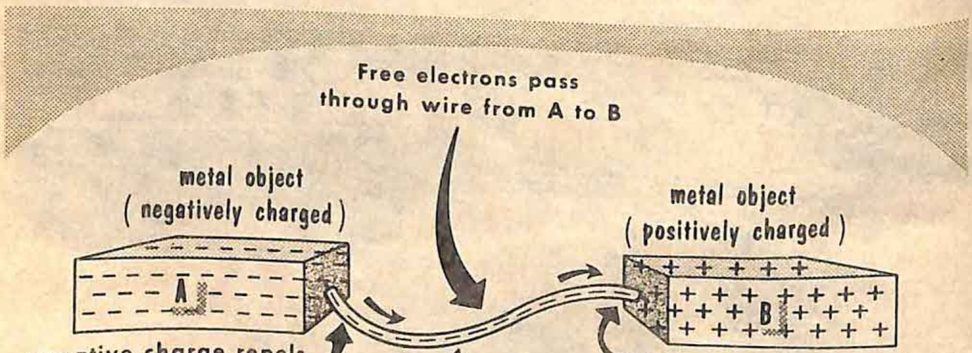

LIGHTNING IS AN ARC DISCHARGE

If all the surplus electrons on the negatively-charged object move over to the positively-charged object, both objects become electrically neutral. That is, the charged objects are discharged; the negatively-charged object because it has lost its surplus electrons, and the positively-charged object because it has acquired enough free electrons to neutralize the excess positively-charged atoms (positive ions) of the metal. It is conceivable that not all of the surplus electrons will move to the positively-charged object during the arc, in which case both objects will remain in a charged state, with each now bearing less charge than before the occurance of the arc.

Discharging through a Wire

It is easy to visualize the action of discharging two charged objects by direct contact. The excess electrons on the negative object stream to the positive ions on the positive object. But how does the discharge action take place through a wire which joins two oppositely-charged metal objects? The answer is important to the study of electricity.

Let us assume the following conditions: The negatively-charged object (A) bears great numbers of excess free electrons along its surface. The positively-charged object (B) has an equivalent shortage of free electrons along its surface. Finally, a piece of copper wire is connected between the pieces of metal. When the copper wire joins A and B, the excess free electrons on A have free electrons which they can repel (the free electrons in the wire). Hence, the wire is a path into which the excess free electrons on A can move. Simultaneously, the excess positive ions on B now have free electrons (in the wire) on which they can exert a force of attraction. Thus, the free electrons in the wire feel a force of repulsion at one end and a force of attraction at the other. Actually, the electrons throughout the wire are subject to these forces. The net result is that the excess free electrons on A enter the wire at the same time the excess positive ions on B are pulling free electrons out of the wire. Of course, as excess electrons leave A, the amount of negative charge diminishes, and as they go to B the amount of positive charge diminishes.

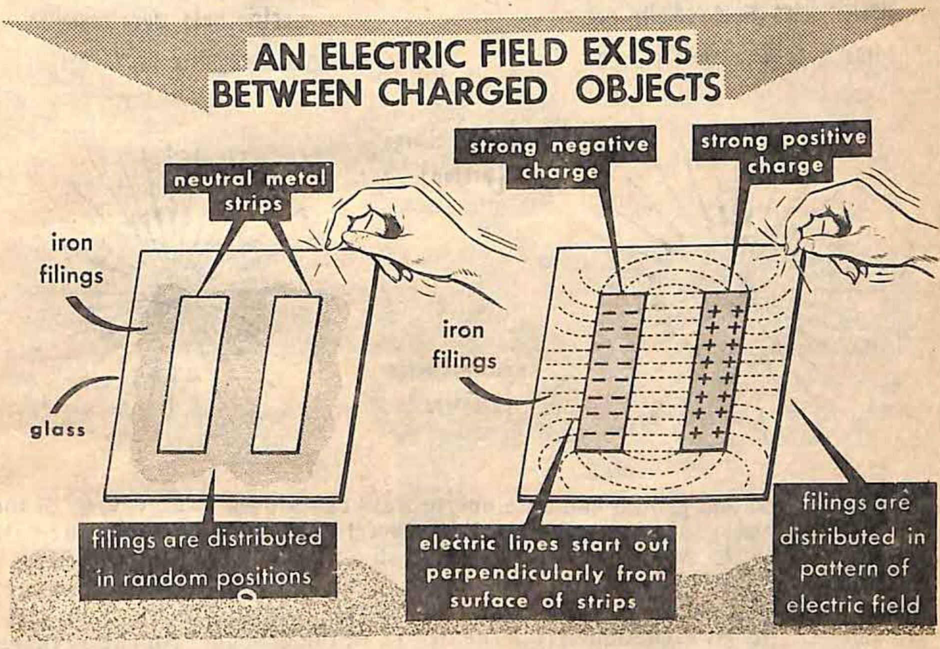

Free electrons pass through wire from A to B
metal object (negatively charged)
metal object (positively charged)
A
B
negative charge repels free electrons in wire
copper wire
positive charge attracts free electrons in wire

DISCHARGING CHARGED OBJECTS THROUGH WIRE
-- as many electrons leave wire and enter B as enter the wire at A

When all the excess electrons have left A and entered B, both strips are fully discharged and no further movement takes place between the two metal objects through the wire. Note that the movement of electrons through the wire is in a single direction -- from negative to positive -- and it happens without any change in the number of free electrons that are present in the wire at any one time, because as many leave the wire as enter it.

Demonstrating the Electric Field Concept

You have learned that the motion between charges or charged objects (attraction or repulsion) is caused by the presence of an electric force. We also said that the charging process was the equivalent of storing electrical energy. But where is the force which moves charged objects? And where does the storage of electrical energy take place? Strangely enough, both are found in the same place -- in the space between the charged objects. This is explained by the concept of the electric field of force, also known simply as the electric field. The space between and all around charged objects is filled with electrical energy--the energy of the electric field that is associated with the charge on the objects. This energy can do work.



AN ELECTRIC FIELD EXISTS BETWEEN CHARGED OBJECTS

strong negative charge
strong positive charge
neutral metal strips
iron filings
iron filings
glass
− −
+ +
filings are distributed in random positions
electric lines start out perpendicularly from surface of strips
filings are distributed in pattern of electric field

It can be demonstrated in the following way. Assume two electrically-neutral parallel-positioned metal strips cemented onto a pane of glass. Now we drop iron filings onto the plate, and tap the glass slightly. The filings occupy random positions. That is, nothing happens! Now, remove the filings and give one metal plate an exceptionally strong negative charge and the other plate an equally strong positive charge. Then drop the filings onto the plate and tap the glass. A distinct line pattern will be seen between the metal strips and around them. Something has happened! The unlike charge given to the two plates has created an electric field between and around the metal strips. The electrical energy that constitutes the field acted on the filings and made them line themselves up in a special way. The field exerted mechanical force. If the two charged strips could move, they would move towards each other.

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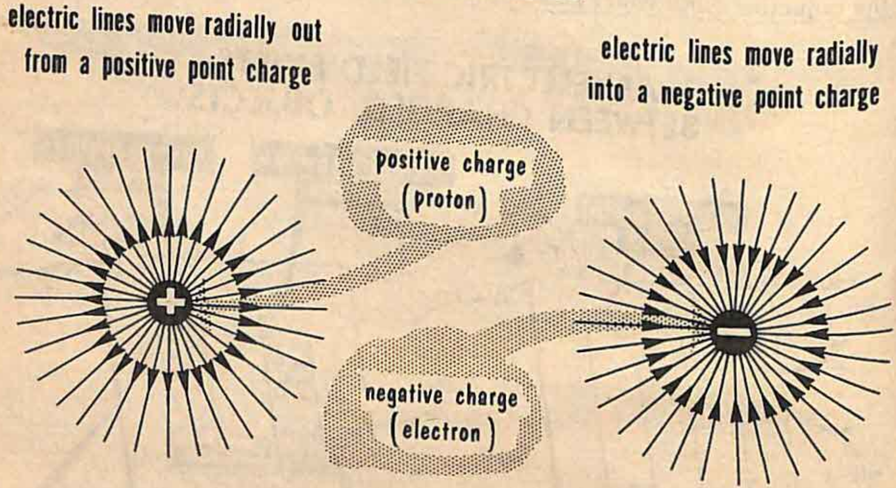
Electric Lines of Force

The electric field between the two charged metal strips shown on the preceding page has a distinct line pattern. One gathers the impression that the iron filings acted on by the energy in the electric field aligned themselves along "lines" of energy. It is explained in the following way.

THE ELECTRIC FIELD AROUND POSITIVE AND NEGATIVE POINT CHARGES


electric lines move radially out from a positive point charge
electric lines move radially into a negative point charge
positive charge (proton)
+
negative charge (electron)
−

Every electron and proton has an electric field of its own. The energy of the fundamental charge is in this field. The electric field occupies the space all around the charge. Michael Faraday, an Irish scientist, pictured this field in a certain way. He visualized the field as being made up of "pencils of energy" which can conveniently be illustrated by innumerable straight lines which radiate outward in all directions from the center of the charge. He called these lines electric lines of force, or simply, lines of force.

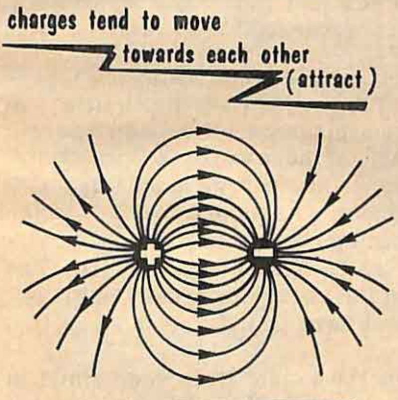
Faraday said that a line of force behaved in certain ways. It had a direction of action; it exerted force in the direction in which it pointed, as indicated by an arrowhead drawn on the line. The direction was, and is (by arbitrary convention) that in which it would make an imaginary positive test charge move. So it pointed away from the proton and toward the electron. Another accepted form of behavior of lines of force is that those lines which advance in the same direction repel one another. A third form of behavior which he conceived was that lines of force which joined unlike charges behaved like stretched rubber bands that always wanted to contract. So, when we say that unlike charges attract, it is the action of the lines of force in the electric field between the charges that pulls them together. When we say that like charges repel, it is the force of repulsion between the lines of force going in the same direction that move facing charges apart.

Lines of Force (Cont'd)

The lines of force concept is a ready means for explaining the apparent absence of electrical effects around electrically-neutral objects, and the electric field around charged objects. Interestingly, an electric field exists around the electrons and protons even in an uncharged object, but the fields have equal intensity and are opposite in direction of action at all points equidistant from the charge. One charge offsets the effects of the other everywhere; therefore, there is no detectable electric field surrounding the object. On this basis, an electrically-neutral atom is considered as having no external electric field. When the process of charging causes an accumulation of electrons on one object and positive ions on the other, each charged object has its own electric field, but two fields acting on each other produce a single net electric field between them.

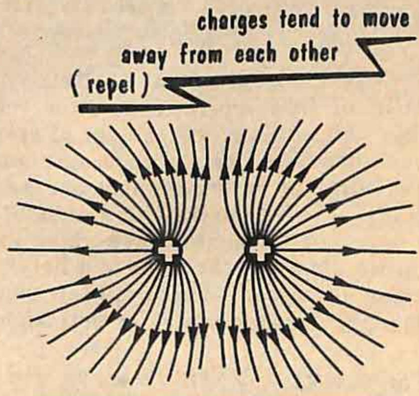
In the case of the positive ions, each ion contains more protons than electrons; hence, it has a net electric field, that of the surplus protons. The energy of this field is detectable beyond the limits of the ion. The same condition is true in the case of the negative ion, except that now the electric field is that due to the excess electrons.

Electric Lines Around Equal But Unlike Charges



All lines terminate at negative charge

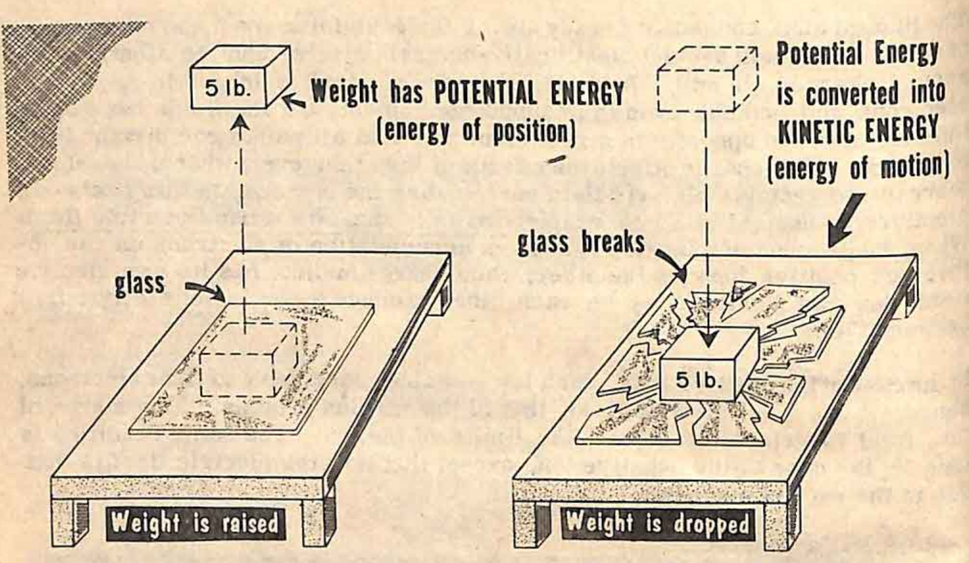
Electric Lines Around Two Equal Positive Charges



All lines terminate at negative charges induced on nearest uncharged objects

As to the line formation of the electric field between the parallel metal strips, it follows the reasoning of the lines of force concept. Actually, there are innumerable lines of force between the strips. The lines of force are substantially parallel between the strips, because the mutual force of attraction between them straightens them.

Potential and Kinetic Energy



MECHANICAL DEMONSTRATION OF POTENTIAL AND KINETIC ENERGY

In the study of practical electricity, we are concerned mainly with the movement of free electrons and the conditions which govern their movement. In this connection, the subject of electricity has a language all its own wherein certain words identify particular conditions. One of these words is "potential." Potential is an abridgment of "potential energy," the energy associated with position. To illustrate this, consider the following. Assume a 5-pound weight resting on a pane of glass which in turn is resting on a table. Now you raise the weight above the glass to a height of say, 6 feet. Then you let it fall. The glass shatters. Where did the weight acquire the energy to break the glass? The answer is simple, even though you may not have thought much about it.

The energy to break the glass was acquired by the weight from your effort in lifting it against the gravitational pull of the earth. This pull accounts for everything falling to the ground, and if it were possible to do so, falling towards the center of the earth. You did work on the weight; that is, you gave energy to the weight when you raised it above the glass. You gave the weight potential energy--the energy of position. The higher you raise the weight above the table, the more work is done on it and the greater is the amount of potential energy stored in the weight. When you allowed the weight to fall, the potential energy was converted to kinetic energy--the energy of motion. When the weight struck the glass, the kinetic energy was changed into heat energy, sound energy, and mechanical energy, all of which are related to the actual physical breaking of the glass and the sound which accompanies the action.

Potential (Cont'd)

Let us now assume that we remove free electrons from an object by any one of the charging processes described, and pass these electrons on to another object. Whatever the method used, the displacement of the electrons requires the application of energy to make them move against either the force of attraction of the positive ions remaining after the electrons have been taken away, or against the force of repulsion from other free electrons which are on the surface to which the electrons are being transferred. The displaced electrons now have acquired potential energy. The greater the displacement, the greater is the amount of work that must be done, and the greater the potential energy acquired by the displaced electrons.

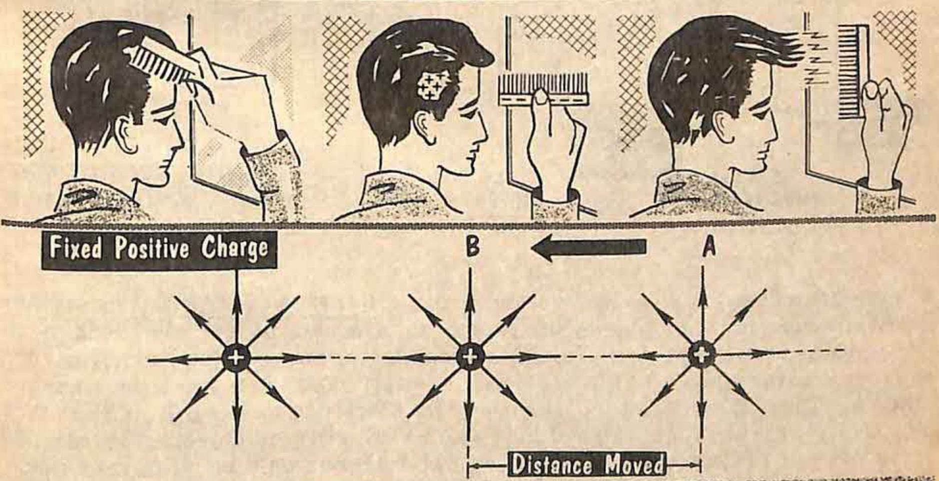
Now, if we arrange for the displaced electrons to go back to where they were, the potential energy is converted to kinetic energy (the energy of motion) and the moving charges can do work. The higher the potential of the charge at any point, the more work can be done when the potential energy is converted into kinetic energy. We save time by referring to the point or place where the charge or charges exist as being at a certain "potential" relative to some reference point, rather than describing it in terms of potential energy.

ELECTRICAL DEMONSTRATION OF POTENTIAL AND KINETIC ENERGY

combing hair charges comb negatively by removing negative charges from hair

displaced electrons on comb now have POTENTIAL energy

potential energy is converted to KINETIC energy by bringing comb near hair --arcing often takes place, heard as "crackling"

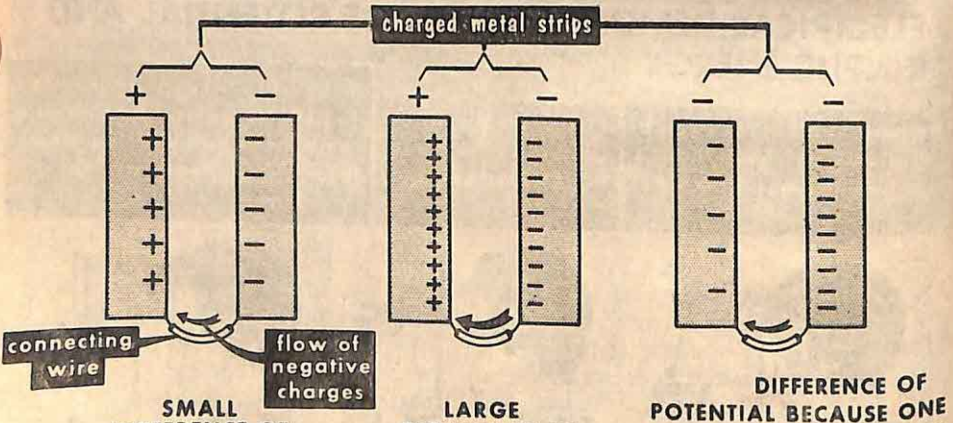


Positive charge at point B has potential equal to Work Done in moving it from point A to point B in opposition to repulsive force of fixed positive charge.

Difference of Potential

Another phrase encountered very often in electricity is "difference of potential." It, too, is related to the movement of free electrons. Difference of potential expresses a situation which determines the tendency of free electrons to move from one place to another. When we accumulate an excess of free electrons on an object and create a shortage of free electrons on another, we create a difference of potential between these two charged objects. You can consider the objects as charged metal strips, if you desire. Given a path between these two objects, free electrons would move from the "negative" strip to the "positive" strip. The greater the excess of free electrons on one strip and the more the shortage of free electrons on the other, the greater is the difference of potential between the two strips and the stronger would be the tendency of the free electrons on the negatively-charged strip to go to the positively-charged strip.

CHARGES TEND TO MOVE BETWEEN TWO POINTS THAT ARE AT DIFFERENT POTENTIALS



SMALL DIFFERENCE OF POTENTIAL

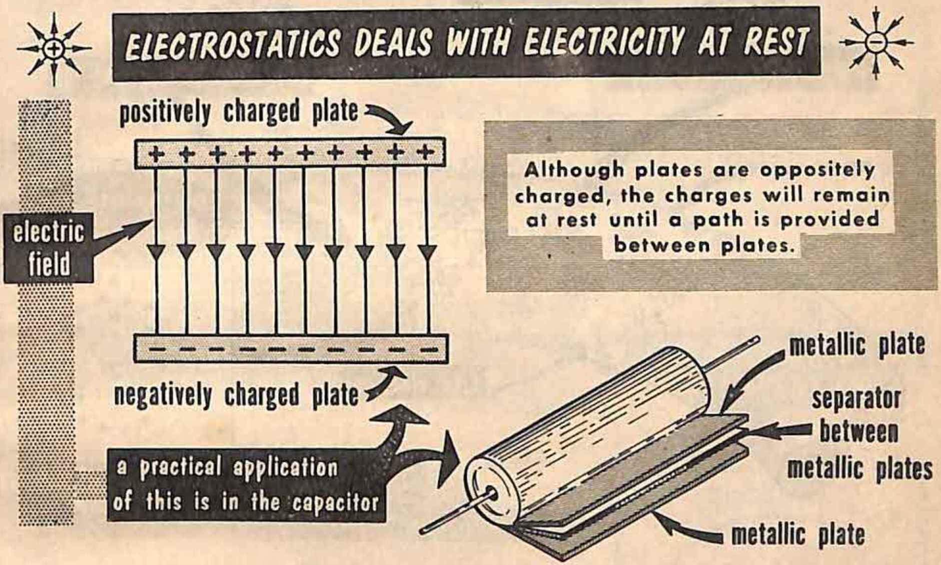
LARGE DIFFERENCE OF POTENTIAL

DIFFERENCE OF POTENTIAL BECAUSE ONE STRIP IS MORE NEGATIVE THAN THE OTHER

It is important however, to understand that a difference of potential exists between any two points or places where unequal amounts of free electrons exist. Conceivably, two metal strips (or any other objects) may be charged negatively, one less than the other. A difference of potential exists between these charged objects. Thus, there would be a tendency for electrons to move from the more negatively-charged object to the less negatively-charged object until both objects were at the same potential, after which there would be no further tendency of the electrons to move between the two charged objects. In other words, and this is a very important condition, movement of free electrons through the wire that connected the two metal strips described several pages back occurred while a difference of potential existed between them.

Static Electricity and Electrostatics

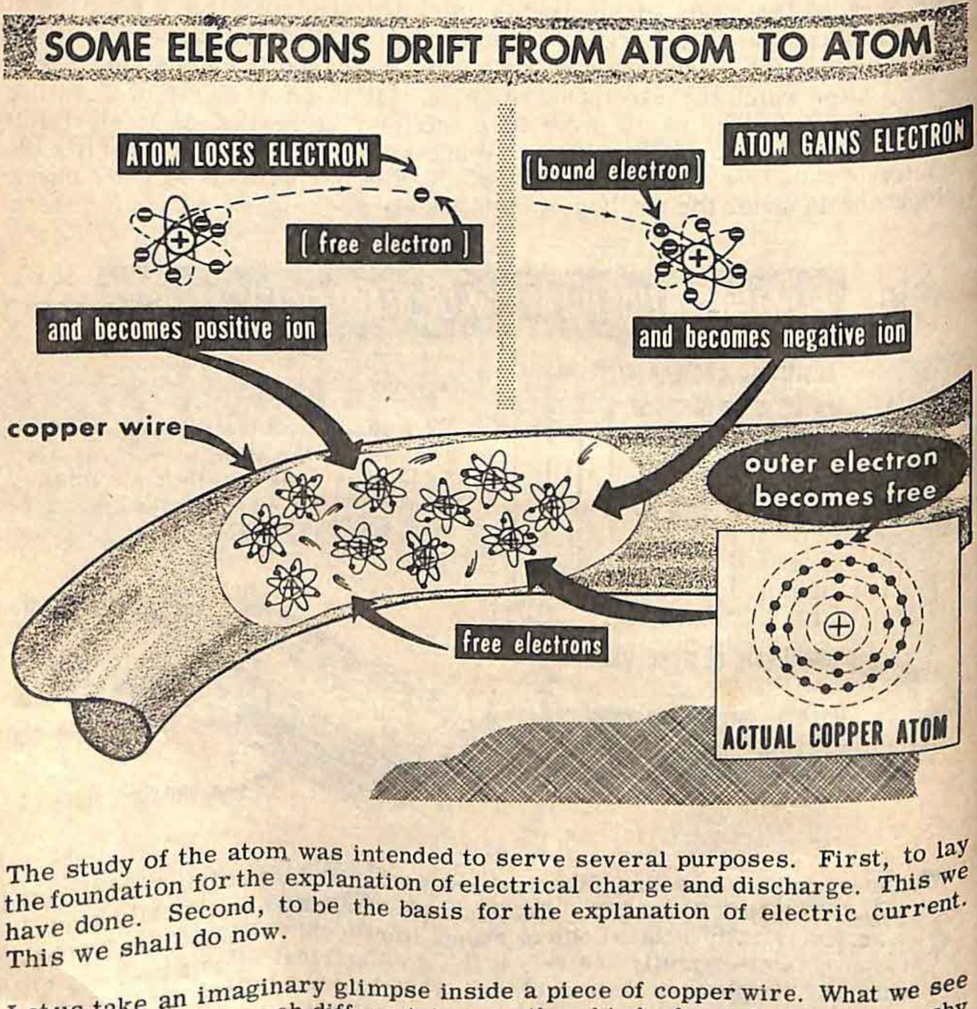
One area of the study of electricity is called electrostatics. We have discussed charging and discharging. Whether the method of charge was by friction, contact, or induction, electrons were displaced from one object to another, after which the electrons came to rest at a new location, creating a charged state. The name given to electricity at rest is static electricity, and the broad subject of charging and discharging (the behavior of static electricity) is called electrostatics. The study of electric fields between charged objects falls under the heading of electrostatics.


ELECTROSTATICS DEALS WITH ELECTRICITY AT REST
positively charged plate
+ + + + + + + + + +
electric field
Although plates are oppositely charged, the charges will remain at rest until a path is provided between plates.
– – – – – – – – – –
negatively charged plate
a practical application of this is in the capacitor
metallic plate
separator between metallic plates
metallic plate

We must not confuse the electrically-neutral condition of an object with the meaning of electricity at rest. Electrical phenomena is not usually associated with an electrically-neutral object except to recognize that it can be charged. But when it is electrically neutral, it has no electrical effects because for all intents and purposes it has no electrical field. In addition, it is important to understand that while a metallic object contains a tremendous number of free electrons in motion, when this object is charged by acquiring electrons, these surplus electrons are (to all intents and purposes) at rest along the surface of the metal.

There are practical reasons for having emphasized the phenomena of charging and discharging. Charging an object is the equivalent of storing electrical energy on the object; discharging an object is the equivalent of releasing the electrical energy. The practical devicewhich does this in radio equipment, and about which you will learn more later, is called a capacitor (also known as a condenser). The purpose of a capacitor is to store electrical energy and to release it when it is needed. As we will learn, electrical charges also play an important role in the operation of tubes and transistors.

Free Electrons and Electric Current

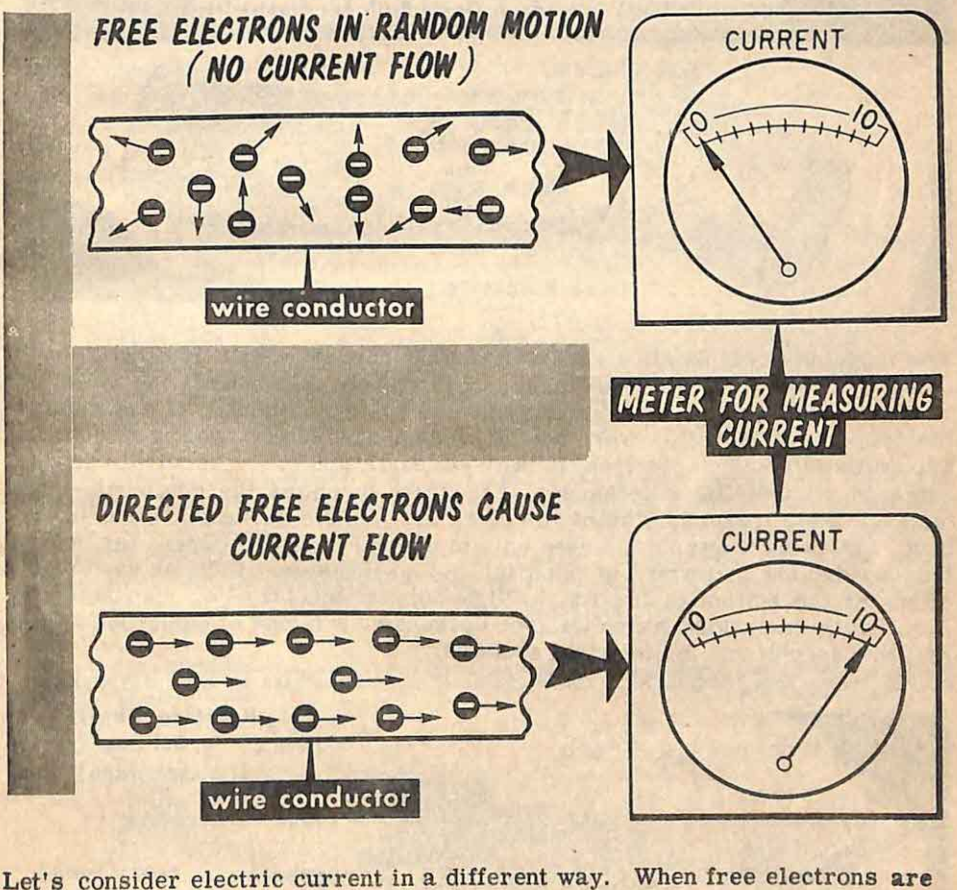


The study of the atom was intended to serve several purposes. First, to lay the foundation for the explanation of electrical charge and discharge. This we have done. Second, to be the basis for the explanation of electric current. This we shall do now.

Let us take an imaginary glimpse inside a piece of copper wire. What we see would not be too much different in any other kind of metal. The atoms shy electrons (more correctly known as positive ions) perform a to-and-fro motion over a very limited distance each side of a "fixed" position. Although describing a vibratory motion, we can, for all purposes, consider the ions as being fixed in location in the wire. In between, a host of free electrons drift slowly in all directions--as many moving in one direction as in the opposite direction. While performing this motion, the free electrons attach themselves momentarily to the ions, and even to atoms which have acquired the balancing electron--only to be freed again a moment later. The free electrons collide with each other, as well as with atoms. This is an important phenomenon, as you shall soon learn. Obviously, metal contains wandering negative electricity (wandering electrons) but it is not usable electricity as it is. We must change electron movement from random to controlled. Then it is electric **current**.

Free Electrons and Electric Current (Cont'd)

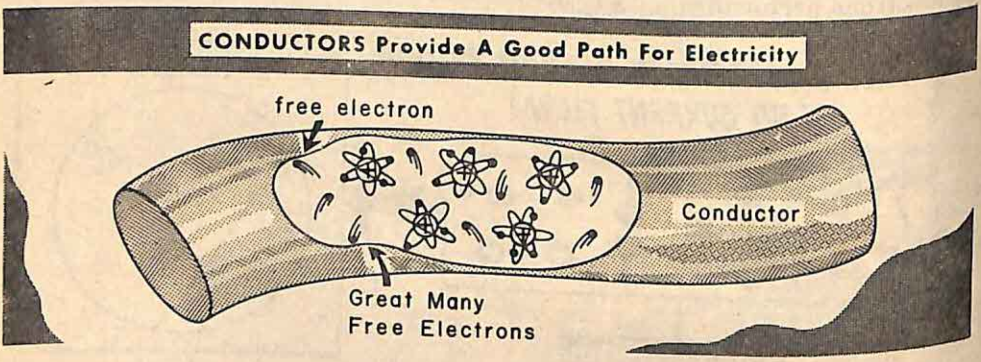
A few pages back, we described the motion of free electrons through a wire connected to two metal strips charged with unlike electricity. The direction of electron flow was from the negative to the positive strip. Such movement was a controlled motion--it had a definite direction--a singular direction throughout the wire. Although the flow of electrons did not last for long, it did constitute electric current while it lasted. We define electric current as free electrons performing a controlled motion.


FREE ELECTRONS IN RANDOM MOTION (NO CURRENT FLOW)
CURRENT
0
10
wire conductor
METER FOR MEASURING CURRENT
DIRECTED FREE ELECTRONS CAUSE CURRENT FLOW
CURRENT
0
10
wire conductor

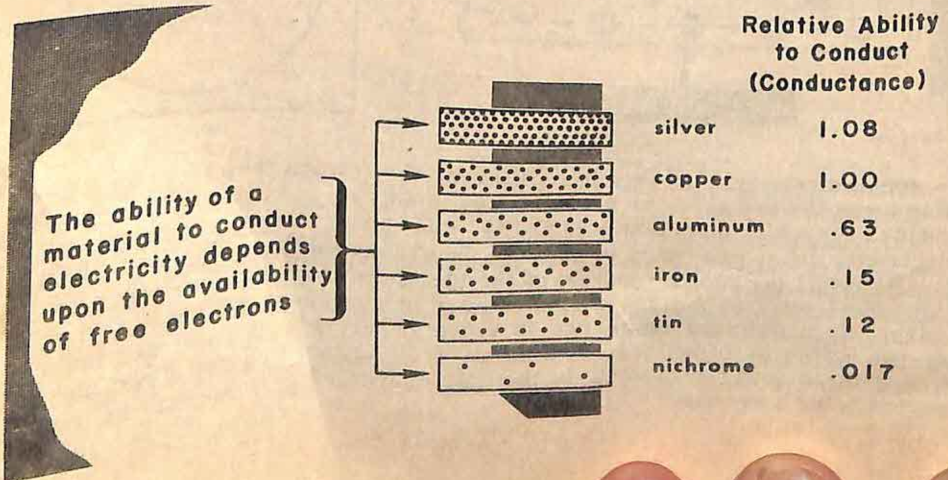
Let's consider electric current in a different way. When free electrons are drifting at random in a wire, as much charge (electricity) moves in one direction as in the opposite direction. There is, therefore, no continuous delivery of electricity from one point to another in a constant direction through the wire. But when the random motion of the electrons is changed to controlled motion, electricity is delivered continuously in a constant direction through the wire. Such delivery of charge is electric current. As you will learn later, two important considerations of electric current are the direction of flow, and the quantity of electricity that is transported in a period of time--the period being 1 second.

Conductors

Based on the atomic concept of matter and the electrical makeup of the atom, all things are made of electricity. Yet, all materials are not equally good as paths for electricity (electric current). Conductors is the name assigned to a broad category of materials through which a practical amount of electric current can flow under normal conditions. Most conductors are metallic.


CONDUCTORS Provide A Good Path For Electricity

The usefulness of metal to conduct electric current stems from the abundance of free electrons in the material, the free electrons being available to be moved through the metal when the material is part of a complete electrical system. However, not all metals are equally good conductors. The availability of free electrons for a given length and cross section is not the same in all metallic substances. The chart indicates the commonly-used metals in their order of suitability as paths for electric current. Silver is the best, but being expensive is used only in special cases. Copper, the second best conducting material, is plentiful and inexpensive; hence, is used most often. At the bottom of the list is Nichrome, a special alloy manufactured specifically to perform as an inferior conductor. It is one of numerous alloys that find special use in electrical systems.

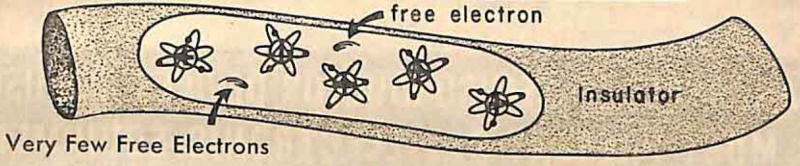


	Relative Ability to Conduct (Conductance)
silver	1.08
copper	1.00
aluminum	.63
iron	.15
tin	.12
nichrome	.017

Insulators

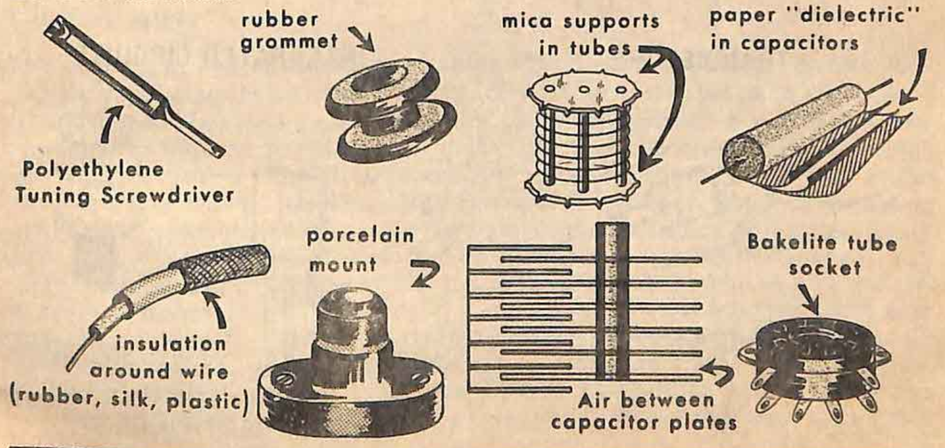
Insulators is the name given to a special group of materials that provide extremely poor paths for electric currents under all normal conditions. In fact, their function is to prevent the flow of electric current. To understand the basis of action of insulator materials, think of an atom whose electrons are bound to the atomic structure; in other words, the material contains very few free electrons. Since there are very few free electrons per given length and cross section of the material, there is very little charge which can be delivered from one point to another. No material is completely void of free electrons. But if they are so few in number, relatively speaking, that a practical and useful amount of electric current cannot flow under normal conditions, we consider the material to be an insulator. Examples of such substances are plastics, glass, mica, mineral oil, rubber, dry paper, dry wood, cotton, and ceramic substances. The above references are not in the order of their suitability as insulators.

INSULATORS Provide A Poor Path For Electricity



Let us clarify some points regarding the names associated with insulator materials. The material itself is called an insulating material, but when it is shaped into some form--large or small--and sometimes used as a support for wires carrying electric current, it is called an insulator. Another word for an insulator is dielectric. If the material is used as a covering around wires that carry electric current, it is called insulation.

ELECTRICAL INSULATION USED IN RADIO


rubber grommet
mica supports in tubes
paper "dielectric" in capacitors
Polyethylene Tuning Screwdriver
porcelain mount
Bakelite tube socket
insulation around wire (rubber, silk, plastic)
Air between capacitor plates

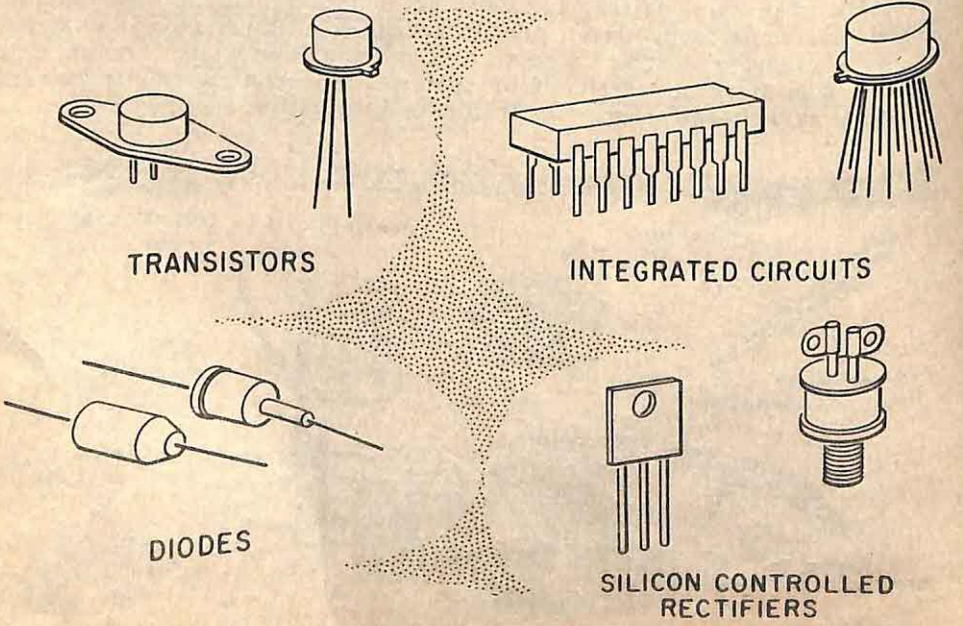
Semiconductors

There is a special group of materials that are neither good conductors nor good insulators. These materials are called semiconductors, and the two most widely used semiconductors are silicon and germanium.

Our so-called "space-age" solid-state electronics would not have been possible without semiconductors. Semiconductor devices, such as transistors, integrated circuits, light-emitting diodes, and solar cells, make space travel and space communications possible; they also make pocket radios, and even pocket electronic calculators, possible. Almost all home radios, and most TV's, use semiconductor devices. In fact, the list of electronics equipment using semiconductors is almost endless.

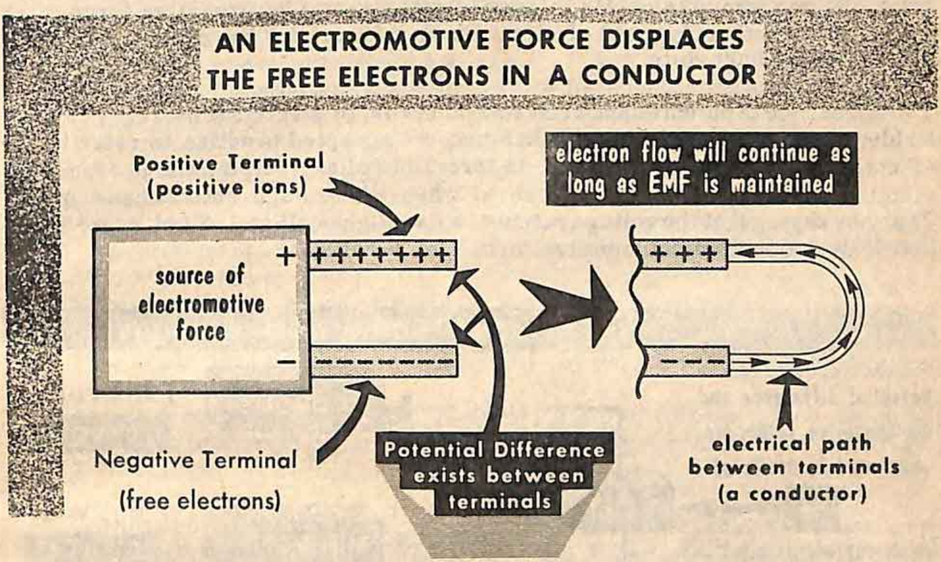
An understanding of present-day radio and electronics requires a firm understanding of semiconductors. For now, however, you will be concerned only with conductors and insulators. Later you will study semiconductors in great detail. In fact, Volume 5 is devoted entirely to semiconductor principles and devices.

MANY TYPES OF SEMICONDUCTOR DEVICES ARE USED IN MOST PRESENT DAY ELECTRONIC EQUIPMENT



Electrical Pressure and Electromotive Force

Q: How is the random motion of free electrons in a conductor changed to the controlled motion that is electric current? A: By the application of electrical pressure which is known as electromotive force. It is abbreviated emf, and pronounced ee-em-eff.


AN ELECTROMOTIVE FORCE DISPLACES THE FREE ELECTRONS IN A CONDUCTOR

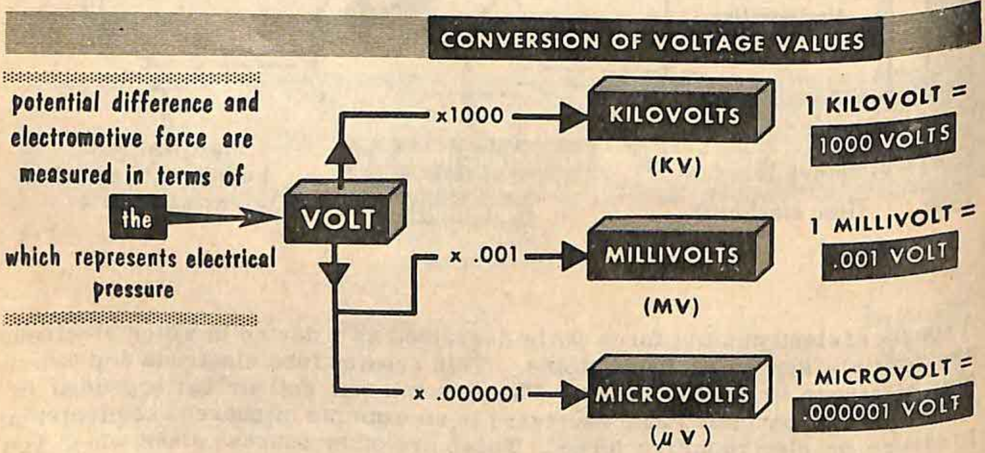
A source of electromotive force can be described as a device in which electrons are forcibly separated from atoms. This creates free electrons and atoms shy electrons or positive ions. The conventional cell or battery used in flashlights and portable radio receivers is an example of sources of electrical pressure or electromotive force. There are other sources about which you will study later.

The separating action referred to above takes place inside the device continuously while the device is functioning. The result corresponds to an accumulation of free electrons on the "negative" terminal (usually designated by the symbol -) and atoms shy electrons on the "positive" terminal (usually designated by the symbol +). The displaced free electrons are attracted to the atoms that are shy electrons (unlike charges attract each other), but they cannot do so by any path inside the device. The chemical action inside a battery prevents this. But if we provide some sort of electrical path outside the battery, connected between the negative and positive terminals, there will be a movement of free electrons between the battery terminals via the external path in a particular direction -- from the negative to the positive terminal. This directional quality of the action is called polarity. The electrical force acting on the electrons accumulated on the negative terminal urging them to the atoms that are shy electrons on the positive terminal is the electromotive force developed by the chemical action in the battery.

Unit of Electromotive Force (the Volt)

If we were speaking about water pressure or air pressure, we would refer to the amount of pressure in terms of "pounds per square inch." In the case of electrical pressure, or more correctly stated, electromotive force, the unit used is the volt. The actual amount of voltage is expressed by a number. Thus, the output of a flashlight cell is rated at an electromotive force of 1.5 volts; the modern automobile battery is rated at an electromotive force of 12 volts. Some other sources of electromotive force may be rated at 10 volts, 120 volts, or 5000 volts.

The difference of potential between two points in an electrical system can also be identified in terms of volts. It has become accepted practice to refer to the electromotive force of a device in terms of voltage output, the presence of electromotive force being understood when the voltage reference is made. Thus, by saying that the voltage output of a flashlight cell is 1.5 volts, we mean that it develops an electromotive force of 1.5 volts.



The voltages encountered in radio equipment involve a very wide range. Voltages may be as high as several thousand volts or as low as a fraction of a millionth of a volt. Sometimes, it is convenient to state them as a number and a word prefix having a numerical significance. For instance, it is quite common to use the prefix "kilo" to mean 1000. In other words, 1 kilovolt (abbreviated kv) means 1000 volts, and 10 kilovolts means 10,000 volts. When the voltage value is between 1 and 999, the amount is expressed as a simple number; beyond 999, the prefix kilo can be used.

Voltages less than 1 volt are sometimes stated as a decimal and sometimes by a number associated with a prefix. For instance, the prefix "milli" means one-thousandth; the prefix "micro" means one-millionth. To state three one-thousandths of a volt, it is customary to say 3 millivolts (3 mv) and, when writing the amount, the decimal .003 volt can be used. In like manner, 100 llionths of a volt would be stated as 100 microvolts (100 µv) and, when it might appear as .0001 volt.

Many materials, when rubbed with other materials, not only attract tiny objects, but exert forces of attraction and repulsion on each other.

Bodies charged with unlike electricity attract each other; bodies charged with the same kind of electricity repel each other; positively-and-negatively-charged bodies attract each other.

Everything is made of two kinds of electricity--positive and negative--and one kind can be separated from the other.

Protons are the fundamental charge of positive electricity; electrons are the fundamental charge of negative electricity.

Electrons are held in their orbits against the pull of centrifugal force by the electrical force of attraction between the protons in the nucleus of the atom and the orbiting electrons.

All matter is composed of one or more of 103 substances known as chemical elements, which are comprised of atoms.

Matter or substances with an excess of electrons are said to be negatively-charged; matter or substances with a deficiency of electrons are said to be positively charged.

Atoms are comprised of positively-charged particles called protons, negatively-charged particles called electrons, and uncharged particles called neutrons.

Metallic objects can be charged by contact or by induction.

Objects bearing unlike charges can be discharged (made electrically neutral) through air (arc discharge), by direct contact, or through a wire.

Every electron and proton has an electric field of its own, which occupies the space around it. The energy of fundamental charge is in this field.

Potential energy is the energy of position; kinetic energy is the energy of motion.

Conductors are materials through which electric current flows under normal conditions; insulators prevent the flow of electric current; semiconductors are neither good conductors nor good insulators.

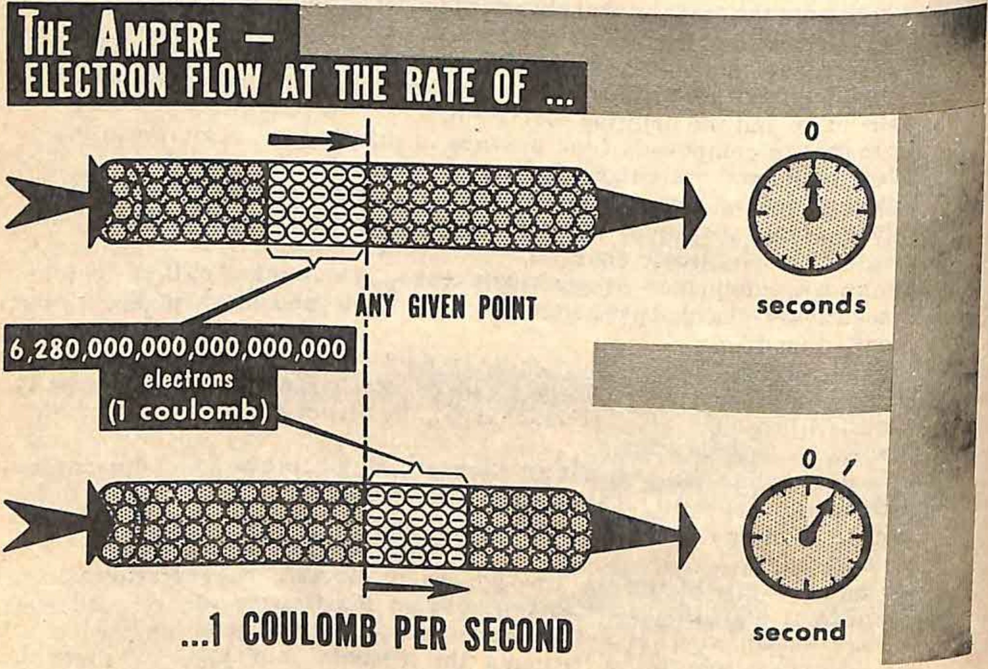
An electromotive force changes the random movement of electrons through a wire to controlled movement (electric current). The unit of emf is the volt. A difference of potential exists between two points or places in an electrical system and is identified in terms of voltage. "Potential" and "voltage" are terms which are used interchangeably.

REVIEW QUESTIONS

1. What are two kinds of electricity called?
2. Define the fundamental laws of attraction and repulsion between two electrical charges.
3. How many elements are there? What is the smallest part of an element?
4. What are atoms comprised of?
5. What is the difference between charging by contact and by induction?
6. Explain what free electrons are.
7. What is an electric current?
8. What is the name given to electricity at rest?
9. Explain what is meant by the "lines of force concept."
10. Define a conductor. Define an insulator. Give examples of each.
11. Define a semiconductor.
12. Which is the better conductor, copper or silver? Which is more widely used and why?

Electric Current (Rate of Flow and Ampere)

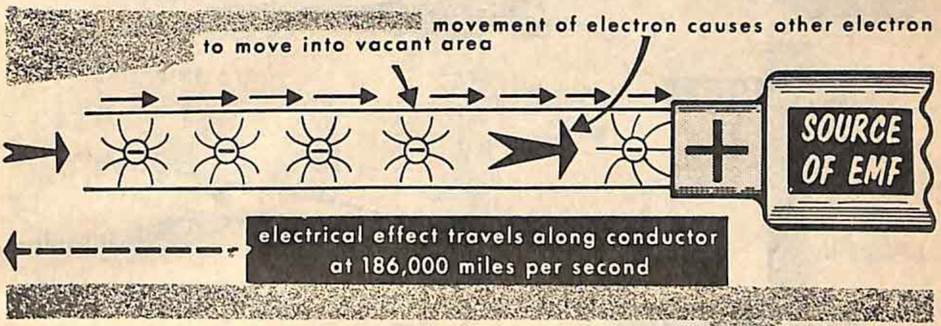
Most electrical devices function by virtue of the electric current which flows through them. An important characteristic of electric current is its rate of flow.

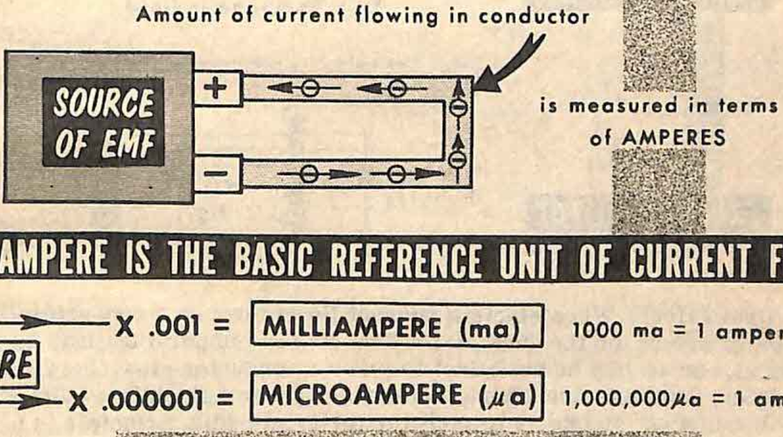


The unit of quantity for electric current is the coulomb, named after the scientist Charles Coulomb (1736-1806). It corresponds to the gallon in liquid measure. Although we seldom mention the equivalency between a gallon of fluid and the number of drops of the fluid that make up the quantity, there is a figure which expresses the amount of electricity contained in a coulomb in terms of the electricity carried by each electron. Specifically, it is the amount of electrical charge equal to 6.28×10^{18} or 6,280,000,000,000,000,000 electrons. (You need not bear this number in mind but it is useful to show that a coulomb is a specific amount of electricity.) It is not sufficient to know the quantity of electricity passing through a device; we must know the rate of flow. In this connection, the unit time reference is 1 second; hence, the rate of flow of electric current is expressed as coulombs per second. This term corresponds to "gallons per minute." However, in the electrical language, we shorten "coulombs per second" to the simple word "ampere," named after the French physicist Andre Marie Ampere (1775-1836). We say that 1 ampere of electric current flows when 1 coulomb of electric charge moves past any given point in 1 second. Note that the word ampere already includes the quantity and the time references. Thus, a reference to 5 amperes means the flow of 5 coulombs of electricity past a given point every second. Another short cut used in engineering language is the letter 'I' to represent the symbol for current.

Velocity of Electrons in a Conductor

We have spoken of current flow as consisting of the movement of free electrons under the influence of an electromotive force. We learned that the individual free electrons moved from atom to atom in the general direction of the positive electromotive force charge, and away from the negative charge. Actually, the forward motion of the individual electrons is not very rapid, but their electrical effect is -- approximately 186, 000 miles per second, the speed of light.


movement of electron causes other electron to move into vacant area
SOURCE OF EMF
electrical effect travels along conductor at 186,000 miles per second


Amount of current flowing in conductor
SOURCE OF EMF
+
−
is measured in terms of AMPERES

THE AMPERE IS THE BASIC REFERENCE UNIT OF CURRENT FLOW

AMPERE X .001 = **MILLIAMPERE (ma)** 1000 ma = 1 ampere

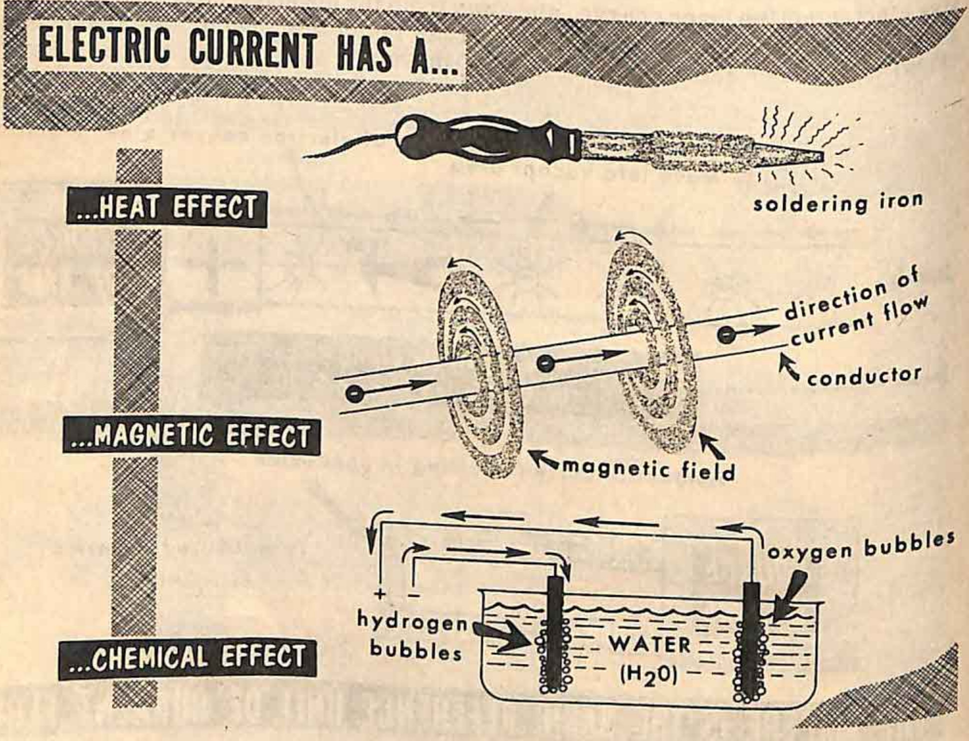
AMPERE X .000001 = **MICROAMPERE (μa)** 1,000,000μa = 1 ampere

When an electron is attracted to the positive terminal, there is a deficiency of negative charge in the area just vacated. A new free electron is attracted to fill the vacancy. This effect travels along the length of the conductor, with the positive terminal attracting and the negative terminal repelling free electrons. Thus, despite the fact that the electrons themselves drift very slowly, the effect of the changes in positions of the electrons is transferred along the conductor, connecting the terminals of the source of emf almost instantly.

In radio, the amount of current flow may be hundreds of amperes in transmitting equipment; but most often, it is in fractions of an ampere. Quantities such as the milliampere (. 001 ampere) and the microampere (. 000001 ampere) are commonly used.

Effects of Electric Current

Although an electric current is invisible, its presence can be detected because of its effects. The greater the amount of current, the stronger the effects.



The Heat Effect. When electric current flows through a conductor, it raises the temperature of the material. The rise in temperature may be inconsequential, or it may be sufficient to make a conductor glow cherry red, as in a toaster, or white hot, as in an electric light or a flashlight bulb. The heat may become so intense as to melt the material--this principle is used in the ordinary "fuse."

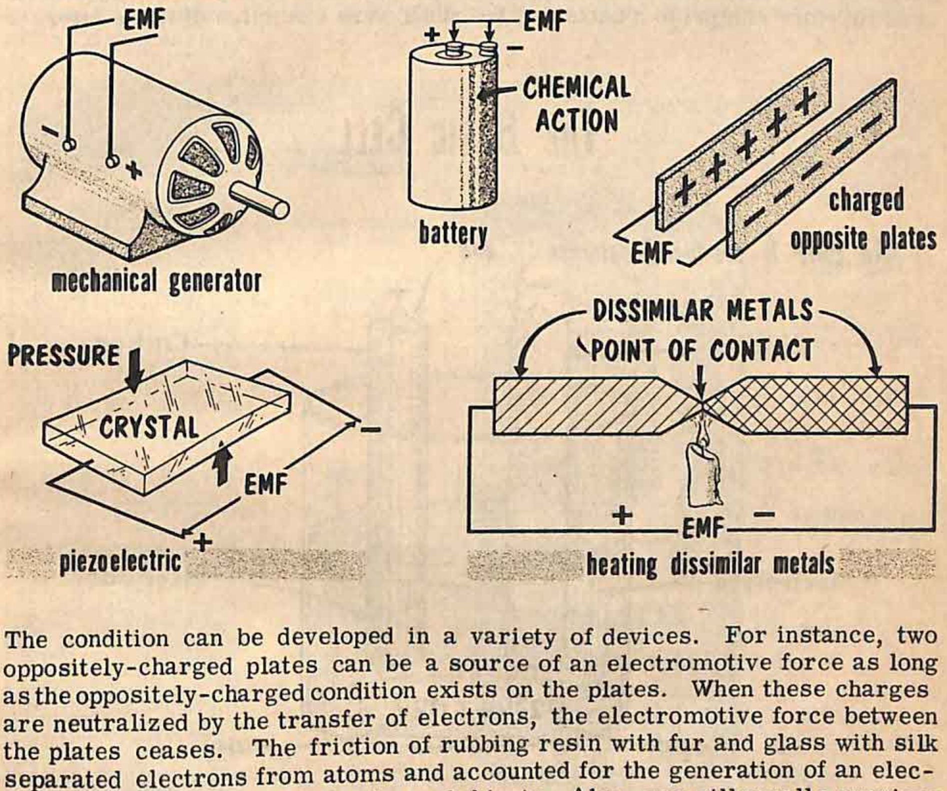
The Magnetic Effect. A second effect of electric current is known as magnetic. Every conductor through which current is flowing is surrounded on all sides by an invisible area of energy known as a magnetic field. The origin of the field is the moving electron, and the intensity of the field depends upon the strength of the current. Of great importance is the fact that the magnetic field is capable of exerting mechanical forces on a variety of metals such as steel, iron, nickel and on materials known as "ferrites." Also, it is capable of exerting mechanical forces on electrons moving in nearby conductors.

The Chemical Effect. A third effect is known as the chemical effect. The passage of electric current through different fluids can cause the breakup (decomposition) of the fluid into its constituent atoms. Also, under certain conditions, electric current passed through acids in which certain metals are immersed can cause decomposition of the metal. This is the basis of electroplating.

The Generation of Electromotive Force

Electromotive force (emf or voltage) was described earlier as being the result of the forcible separation of electrons from atoms, causing an accumulation of electrons (negative charge) at one point, and an accumulation of atoms shy electrons (positive charge) at another point.

AN ELECTROMOTIVE FORCE OR DIFFERENCE OF POTENTIAL CAN BE GENERATED IN A VARIETY OF WAYS



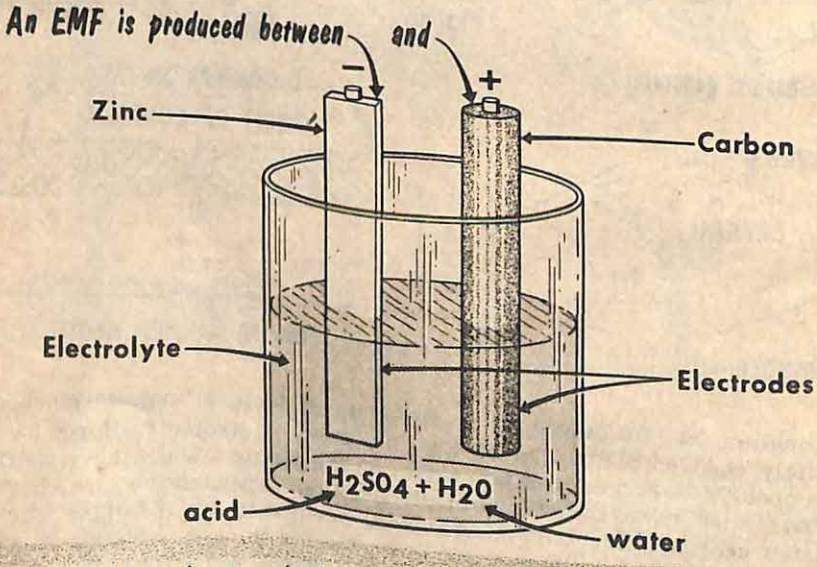
The condition can be developed in a variety of devices. For instance, two oppositely-charged plates can be a source of an electromotive force as long as the oppositely-charged condition exists on the plates. When these charges are neutralized by the transfer of electrons, the electromotive force between the plates ceases. The friction of rubbing resin with fur and glass with silk separated electrons from atoms and accounted for the generation of an electromotive force between these charged objects. Also, you will recall a previous reference to batteries. They generate an electromotive force by internal chemical action, continuing to do so as long as the chemical action continues.

Rotating machines know as generators constitute another category of devices that generate an electromotive force. Later, we shall discuss the method. Still other substances, like slabs of quartz and crystals of Rochelle salts, when subjected to pressure or physical deformation, result in the separation of electrons from atoms within them and so generate electromotive force between their faces. This is known as the "piezoelectric" effect. Two dissimilar metals, placed in contact with each other and with their point of contact heated, will generate an electromotive force at the open ends.

The Primary Cell

Experiments conducted during the 18th century disclosed that when two dissimilar materials like zinc and carbon (or copper used in place of carbon) were immersed in a bath of acid solution (sulphuric acid diluted in water), chemical action produced an electromotive force between the zinc and the carbon (or copper). The materials immersed in the acid were called the electrodes, with the zinc being the negative electrode and the other (carbon or copper) being the positive electrode. The diluted acid solution was called the electrolyte; the whole assembly was called the cell. Often, cells are mistakenly referred to as batteries. Actually, the cell is the basic unit; two or more cells used together comprise a battery. We shall show examples of these later.

THE BASIC CELL



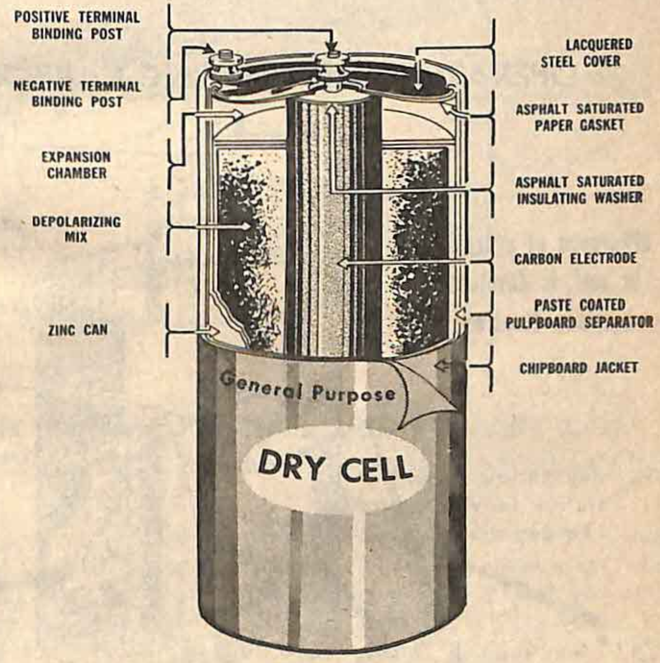
When the + and — terminals are connected externally, current will flow

As to the broad significance of a "primary" cell, it has a particular meaning, this being that the zinc dissolves slowly while the cell is functioning. Eventually, the zinc is eaten away to the extent that it prevents further operation of the cell. When this stage is reached, the cell has exhausted its useful life. In other words, a primary cell is of the kind which has a limited life, after which its operation cannot be restored and the cell as a whole must be disposed of. There are other kinds of cells which will be dealt with separately in this section of the course.

The Zinc-Carbon (Le Clanche) Primary Cell

By far, the most popular and commonly-used primary cell is the zinc-carbon type, sometimes referred to as the Le Clanche cell. In this cell, the positive electrode is made of carbon (C) and the negative electrode is made of zinc (Zn). The electrolyte is a chemical known as ammonium chloride (NH_4C1), often called sal ammoniac. The negative electrode is in the form of a container and holds the entire cell. The positive element is in the form of a carbon rod located at the center of the cell. The electrolyte is mixed with cornstarch or flour to form a paste. Thus, a dry cell is not really "dry." In fact, when the electrolyte drys out, the cell becomes useless. A mixture of finely-ground manganese dioxide (MnO_2) is packed around the carbon electrode to act as a depolarizer.

CONSTRUCTION OF A TYPICAL PRIMARY CELL (ZINC-CARBON)

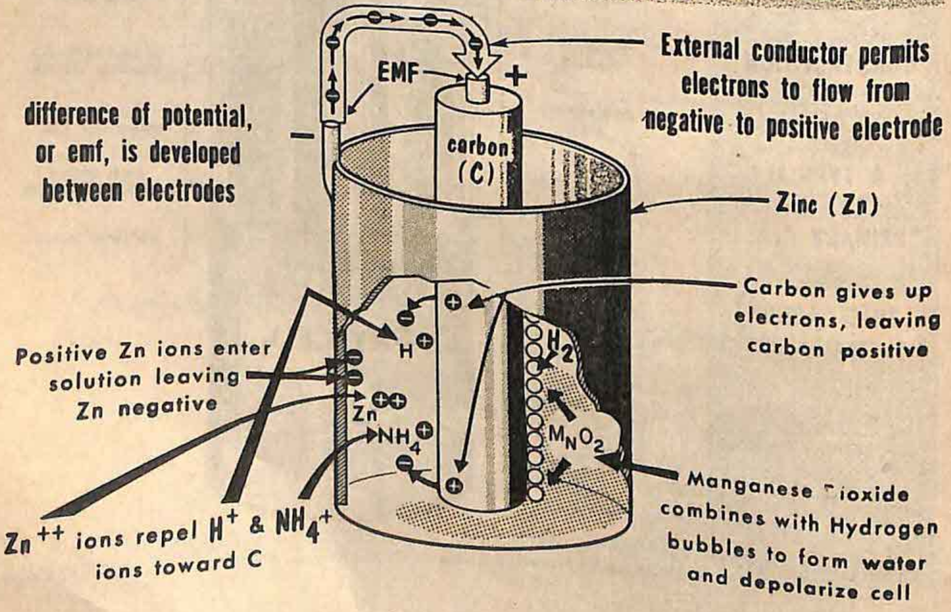

POSITIVE TERMINAL BINDING POST
NEGATIVE TERMINAL BINDING POST
EXPANSION CHAMBER
DEPOLARIZING MIX
ZINC CAN
LACQUERED STEEL COVER
ASPHALT SATURATED PAPER GASKET
ASPHALT SATURATED INSULATING WASHER
CARBON ELECTRODE
PASTE COATED PULPBOARD SEPARATOR
CHIPBOARD JACKET
General Purpose
DRY CELL

When the cell is operating properly, a difference of potential (or voltage) of about 1.6 volts (fully charged) is developed across the positive and negative terminals. As the cell becomes "used up," either by the electrolyte drying out or the zinc electrode being "eaten" away, the terminal voltage will fall off. At about 1.1 volts (discharged), this type of cell becomes useless for most applications -- it cannot be recharged, and must be discarded. Different combinations of dissimilar metals and electrolytes will produce different terminal voltages.

Action in a Primary Cell

Let us connect a conducting wire between the terminals of a zinc-carbon dry cell. In the electrolyte (NH_4C1), ammonia ions (NH_4^+) and chlorine ions ($C1^-$) are present. When the zinc makes contact with the electrolyte, zinc ions (Zn^{++}) enter the solution, each leaving two electrons on the negative electrode. The accumulation of negative electrons constitutes a negative charge on the zinc plate. The Zn^{++} ions in the solution repel the positive hydrogen ions (H^+) and ammonia (NH_4^+) ions that are already there toward the ammonia atoms which collect on the surface of the carbon electrode in the form of gaseous bubbles. The loss of electrons leaves the carbon electrode with a positive charge. The Zn^{++} ions combine chemically with the $C1^-$ ions to form zinc chloride ($ZnC1_2$), a white substance. You may have seen this substance when you removed "dead" cells from a flashlight case. Therefore, the zinc plate is gradually used up to form zinc chloride ($ZnC1_2$) during the operation of the cell.

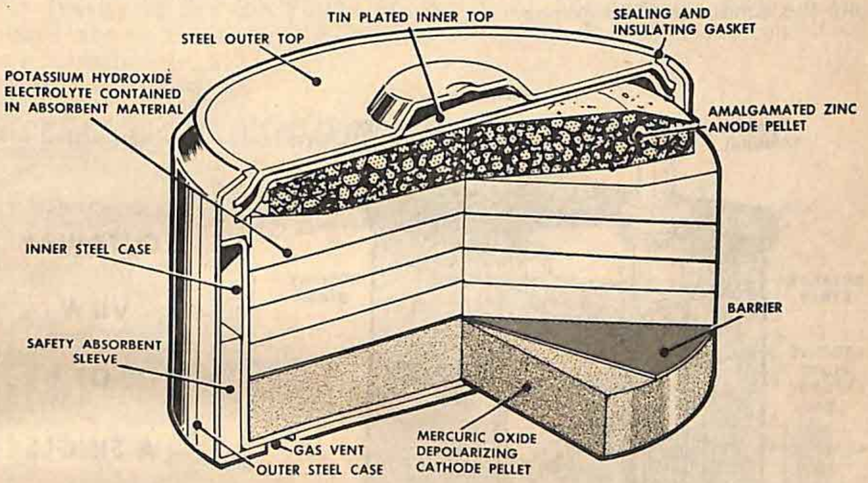
OPERATION OF THE ZINC-CARBON DRY CELL


External conductor permits electrons to flow from negative to positive electrode
EMF
+
−
difference of potential, or emf, is developed between electrodes
carbon (C)
Zinc (Zn)
Carbon gives up electrons, leaving carbon positive
Positive Zn ions enter solution leaving Zn negative
H
H_2
Zn
NH_4
M_NO_2
Manganese Dioxide combines with Hydrogen bubbles to form water and depolarize cell
Zn^{++} ions repel H^+ & NH_4^+ ions toward C

The overcrowded electrons on the zinc plate repel each other. This repulsion, plus the attraction of the positive charge on the carbon plate, results in the creation of the emf of the cell. This emf causes electron, hence current flow, through the external conducting path between the electrodes. The accumulation of hydrogen bubbles over the carbon electrode adversely affects the operation of the cell by blocking normal chemical action. This is called polarization. The manganese dioxide in the electrolyte prevents polarization by combining with the hydrogen bubbles to form water.

Primary Cells (Zinc-Mercury Oxide Type)

Another kind of primary cell is the zinc-mercury oxide type. The cell consists of an amalgamated zinc negative electrode either in powder form or in coiled corrugated strips. The positive electrode consists of a mixture of mercuric oxide and graphite, molded under pressure in a steel cup and assembled into the cell. The electrolyte is a solution of potassium hydroxide and zinc oxide. Cellulose material is used as a separator and maintains the electrolyte in paste form to prevent spilling.


TIN PLATED INNER TOP
SEALING AND INSULATING GASKET
STEEL OUTER TOP
POTASSIUM HYDROXIDE ELECTROLYTE CONTAINED IN ABSORBENT MATERIAL
AMALGAMATED ZINC ANODE PELLET
INNER STEEL CASE
BARRIER
SAFETY ABSORBENT SLEEVE
GAS VENT
OUTER STEEL CASE
MERCURIC OXIDE DEPOLARIZING CATHODE PELLET

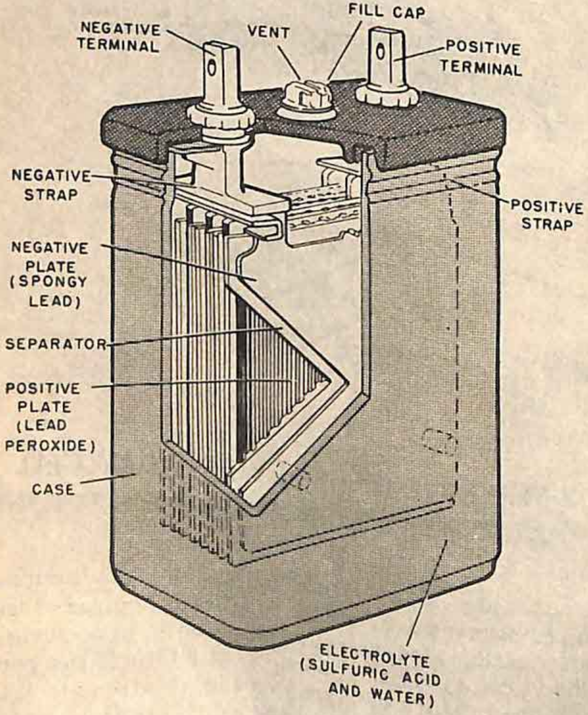
CONSTRUCTION OF THE ZINC-MERCURY PRIMARY CELL

The voltage of this cell when not in use is 1.34 volts, but under normal current drain, the voltage will drop to between 1.31 and 1.24 volts. Compared with most other types of primary cells, zinc-mercury oxide cells have several very desirable features. The voltage over the operating life (discharge cycle) is nearly constant, and its ability to store electrons on the negative electrode is superior to that of the zinc-carbon cell. It has a comparatively high current output which it can maintain for a considerable period of time. Also, storage and shelf life are maintained at higher temperatures. However, zinc-mercury cells are more expensive, and have been in demand mainly where their reduced size makes their use feasible. Some of these applications are: hearing aids, small portable radios, portable communication equipment, electrical test equipment, scientific instruments, and in some applications as a voltage reference.

An interesting feature of this cell is its ability to maintain a relatively constant voltage over its useful lifetime. In many instances, the voltage of this cell is used as a standard with which to check voltage-measuring instruments.

The Secondary Cell (Lead-Acid)

The primary difference between the secondary cell and the primary cell is in the fact that the secondary cell is rechargeable. That is, after the secondary cell has been in use and has discharged, its chemical action can be reversed and cell recharged. The most popular and widely-used secondary cell is the lead-acid "storage" cell, found in automobiles, trucks and a wide variety of vehicles. When fully charged, this cell has an output voltage of approximately 2.2 volts. Automobile batteries generally contain six of these cells. The lead-acid cell is capable of delivering extremely high currents, running into the hundreds of amperes.


FILL CAP
NEGATIVE TERMINAL
VENT
POSITIVE TERMINAL
NEGATIVE STRAP
POSITIVE STRAP
NEGATIVE PLATE (SPONGY LEAD)
SEPARATOR
POSITIVE PLATE (LEAD PEROXIDE)
CASE
ELECTROLYTE (SULFURIC ACID AND WATER)

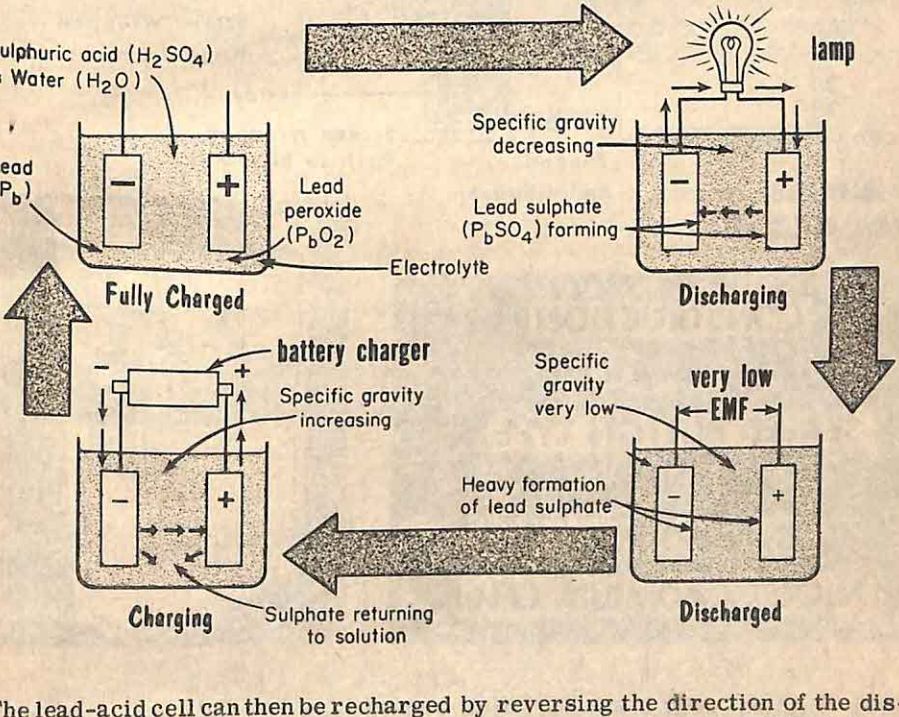
CUTAWAY VIEW OF A SINGLE LEAD-ACID STORAGE CELL

The two dissimilar metals in the lead-acid cell are finely divided or spongy lead (Pb) in the form of a plate, and lead peroxide (PbO_2). The lead is the negative electrode and the lead peroxide the positive electrode. These materials are relatively soft, and are passed into the openings of a grid to form a rugged plate. The electrolyte is sulphuric acid (H_2SO_4) mixed with distilled water (H_2O). A cell consists of several negative and several positive plates interleaved and fitted into a container, together with the electrolyte. The condition of this cell can be checked with a hydrometer which measures the specific gravity of the electrolyte (the weight of the electrolyte as compared to the weight of the water). When fully charged, the specific gravity may be 1.25; when discharged, about 1.1.

Charge and Discharge in the Lead-Acid Cell

Let us look at the chemical action in a lead-acid cell. When fully charged, the negative plates (electrode) consist of lead, and the positive plates, of lead peroxide. The electrolyte is sulphuric acid and water. If we connect a conductor between the positive and negative terminals, current will flow and the cell begins to discharge. During discharge, the acid content of the electrolyte decreases, and lead sulphate ($PbSO_4$) deposits on both the positive and negative plates. The amount of water in the electrolyte increases. This process continues until both the electrodes contain a maximum of lead sulphate and the specific gravity of the electrolyte is very low. At this time, since the two electrodes are no longer dissimilar, the difference of potential across them is at a minimum.

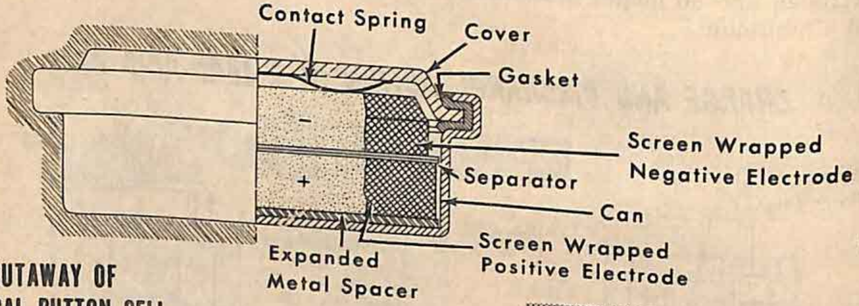
CHARGE AND DISCHARGE ACTION IN A LEAD-ACID CELL


Sulphuric acid (H_2SO_4)
& Water (H_2O)
Lead (P_b)
Lead peroxide (P_bO_2)
Electrolyte
Fully Charged
lamp
Specific gravity decreasing
Lead sulphate (P_bSO_4) forming
Discharging
battery charger
Specific gravity increasing
Specific gravity very low
very low EMF
Heavy formation of lead sulphate
Charging
Sulphate returning to solution
Discharged

The lead-acid cell can then be recharged by reversing the direction of the discharge current. This is done by connecting the positive terminal of the battery to the positive terminal of a battery charger, and the negative terminal of the battery to the negative terminal of the charger. During the charging process, the negative plate returns to lead and the positive plate to lead peroxide. The sulphate returns to the electrolyte and its specific gravity increases. During charge, hydrogen and oxygen are given off, and some water must be added to the electrolyte to replace the water lost. This is the reason you have to add water to your automobile battery on the average of two or three times a year.

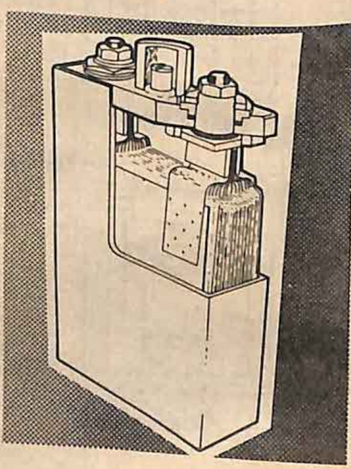
The Nickel-Cadmium Cell

The nickel-cadmium cell is another type of secondary cell that has found considerable use in portable and mobile electronic equipment. It is a mechanically-rugged cell that can withstand overcharging, overdischarging, or standing idle in a discharged condition for a long time. Being a secondary cell, this unit can be recharged after having been discharged. In the charged condition, the positive electrode of a nickel-cadmium cell is a nickelic hydroxide; the negative electrode is metallic cadmium. The electrolyte is potassium hydroxide. The average operating voltage of the cell under normal discharge conditions is about 1.2 volts.


Contact Spring
Cover
Gasket
-
+
Screen Wrapped Negative Electrode
Separator
Can
Screen Wrapped Positive Electrode
Expanded Metal Spacer

CUTAWAY OF TYPICAL BUTTON CELL

CONSTRUCTION OF A SEALED BUTTON TYPE AND SINTERED PLATE NICKEL-CADMIUM CELL



Nickel-cadmium cells come in a wide variety of shapes and types, the most popular being the hermetically-sealed variety available in rectangular, cylindrical and button form, and the sintered-plate construction requiring a vent. In the sintered-plate type, the plates are arranged in groups connected by welded group straps and are separated by layers of fabric. Positive and negative plate groups are intermeshed and placed in plastic containers. During charge and discharge of a nickel-cadmium cell, there is practically no change in the specific gravity of the electrolyte. The electrolyte acts only as a conductor for the transfer of hydroxide ions from one electrode to the other, depending upon whether the cell is being charged or discharged.

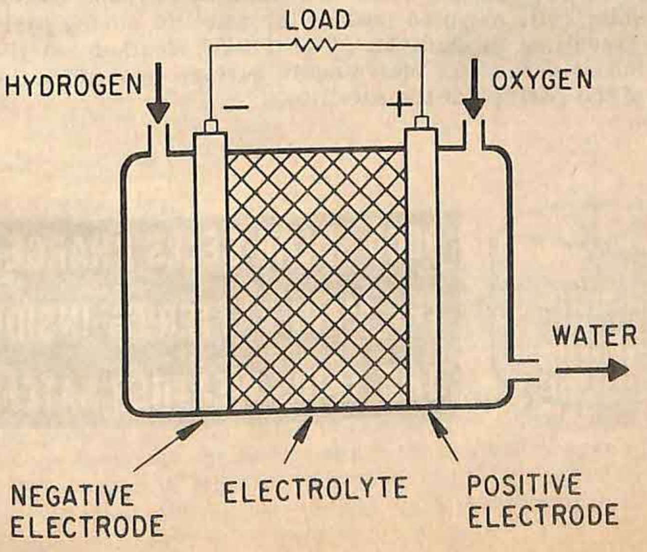
Fuel Cell

In many respects the fuel cell is similar to a lead-acid cell. The electrodes are made from a porous metal such as nickel, and the electrolyte is either an acid or alkaline solution such as potassium hydroxide. In a lead acid cell, energy is stored during the charging process; the energy is then dissipated as it is withdrawn, and the cell then requires recharging. In the fuel cell, however, energy is not stored; it is continuously applied in the form of hydrogen and oxygen, and the cell will supply electrical energy as long as the supply of hydrogen and oxygen lasts.

In operation the hydrogen, under pressure, is forced through the porous negative electrode where it contacts the electrolyte. In the negative electrode the atom of hydrogen, under the influence of the electrolyte, gives up an electron. The electron is withdrawn from the electrode, and the positive ion of hydrogen continues into the electrolyte. At the positive electrode the positive ion of hydrogen, under the influence of the oxygen, recombines with the electrons returning from the load, and at the same time the hydrogen and oxygen combine to form H_2O, water.

The output voltage of a single fuel cell is approximately 1 volt. An important feature of the fuel cell is the byproduct of potable water, important for use in spacecraft. Heat is produced in generating the electrons at the negative electrode; this heat is removed from the cell by the higher pressure of the hydrogen gas. The high pressure of the gas also acts to push the water out of the cell to keep the water from rising to a level that will affect the operation of the cell and reduce its output.

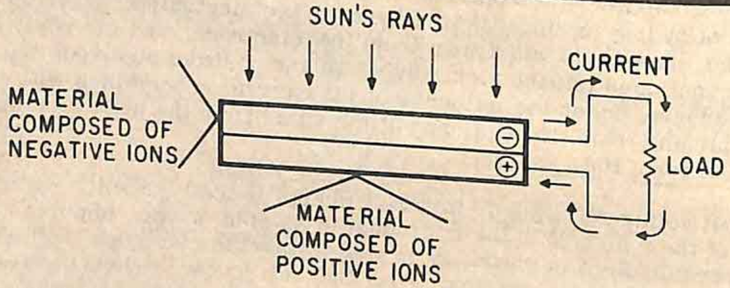
BASIC HYDROGEN — OXYGEN FUEL CELL



Solar Cells

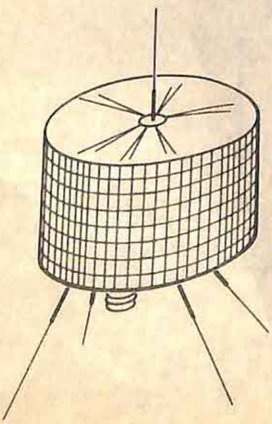
Solar cells are constructed of special semiconductor materials, in which the outermost half of the cell consists of negatively ionized material (excess electrons) and the other half of positively ionized material (lacks electrons). Semiconductor materials are discussed fully in Volume 5. The energy of the sun, or energy from another light source, is used to free the excess electrons in the negatively ionized material. The freed electrons, attracted by the positively ionized material, flow through the load.

A TYPICAL SOLAR CELL


SUN'S RAYS
CURRENT
MATERIAL COMPOSED OF NEGATIVE IONS
⊖
⊕
LOAD
MATERIAL COMPOSED OF POSITIVE IONS

Typical output of a solar cell at sea level on a clear day is 100 milliwatts of power for each square centimeter of surface area. Above the earth's atmosphere the sun's rays have approximately 1/3 more energy, which provides about 130 milliwatts per square centimeter.

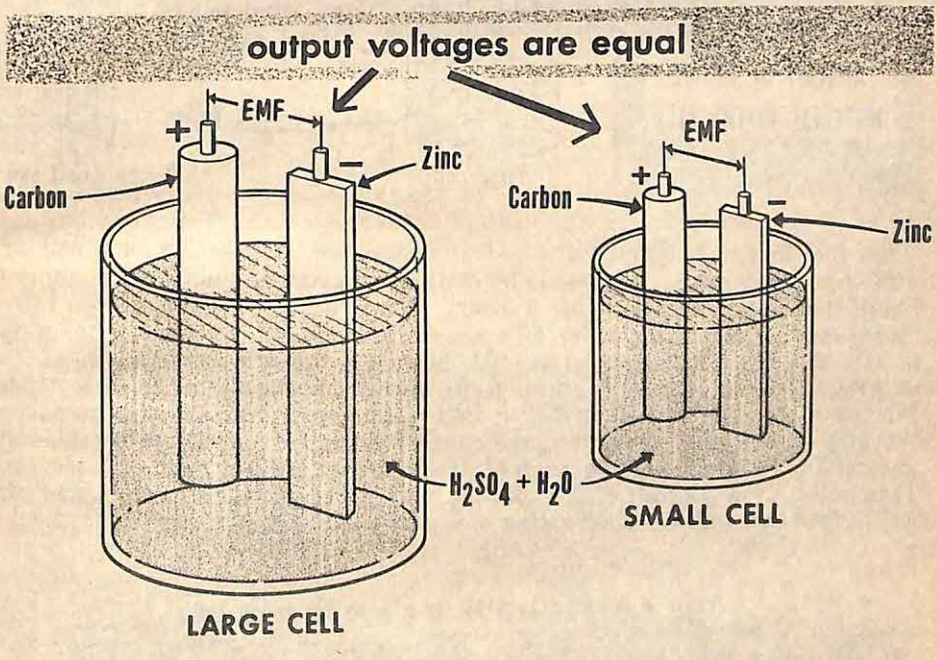
The major use of solar cells is for satellite battery recharging. Satellites are usually powered by large numbers of batteries, such as nickel-cadmium batteries, which are located within the satellite. These batteries are recharged by solar cells mounted outside the satellite during periods when the satellite is travelling in sunlight. The TIROS Weather Satellite has 9000 solar cells mounted over its entire outer surface to capture the sun's rays regardless of the position of the satellite.



9000 SOLAR CELLS CHARGE THE MAIN BATTERIES INSIDE THE TIROS WEATHER SATELLITE

Output Voltage Rating of Cells

An interesting fact about the electromotive force (emf) generated in cells is that the output voltage of a cell depends upon the kinds of materials used in the cell, and not upon the dimensions of the materials. For instance, all zinc-carbon cells use zinc and carbon electrodes, with an electrolyte of ammonium chloride. This is true whether we consider the tiny "pen" type cells or the very large No. 6 cells used for bells and electric trains. The output voltage of both is exactly the same -- 1. 6 volts for a new fully-charged cell. As we will learn later, the big difference between these cells is in the available current output. The same is true of the common lead-acid storage cell. A small cell of this type having a few plates will have an output voltage of 2. 2 volts, the same as a large lead-acid cell having a great many large plates. There are many other different combinations of chemicals that give various voltages, but the quantity of chemicals involved do not affect the output voltage.



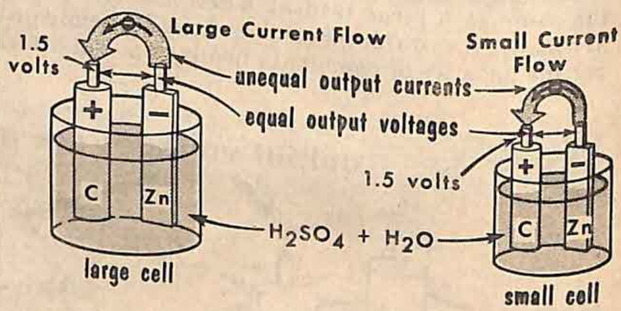
THE OUTPUT VOLTAGE OF A CELL DEPENDS UPON THE KIND OF CHEMICALS USED AND NOT UPON THE QUANTITY OF CHEMICALS USED

To measure the output voltage of a cell, a "voltmeter" is used. This instrument will be covered in detail later in this course. The voltmeter is connected across the terminals of the primary cell and the voltage is read on the voltmeter. The same is true of secondary cells; however, to get a more accurate check of the quality of such a cell, it is common to make the voltage measurement while the cell is discharging, or "under load."

The Current Capacity Rating of Cells

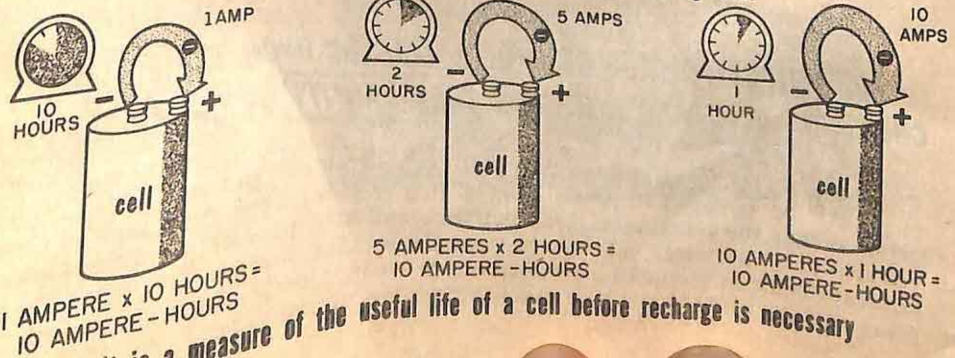
You have learned that if a wire is connected between the negative and positive terminals of a cell, a current will flow through the wire. The fact that electrons leave the cell and enter the wire is the basis for viewing the cell (or a battery of cells) as being a source of current. As long as the proper chemical action continues, the supply of electrons continues. The ability of the cell to supply electrons at a certain rate is referred to as its current capacity. The maximum rate of supply of electrons depends upon the size or amount of active material in the electrodes, assuming proper condition of the electrolyte. This explains why the large No. 6 dry cell can supply more current than the much smaller cell.

THE CURRENT CAPACITY OF A CELL DEPENDS UPON THE AMOUNT OF ACTIVE MATERIAL IN THE CELL



When the current capacity of a cell is expressed, (a practice most common with secondary cells), it is done by stating the maximum number of amperes which the cell will supply for 1 hour. Thus, a 20 ampere-hour cell rating means that the cell will furnish 20 amperes of current for 1 hour, after which it will be in a discharged state. If, however, the rate of discharge is less than the maximum capability, the cell can supply current for more than 1 hour. For example, the 20 ampere-hour cell could supply 1 ampere for 20 hours. Working in the other direction, the current capacity could be proportionately greater for a shorter period, such as 100 amperes for one-fifth of an hour, or 12 minutes. The product of the current in amperes and the time in hours cannot exceed the ampere-hour rating of a particular cell.

THE AMPERE-HOUR is a basis for rating cells

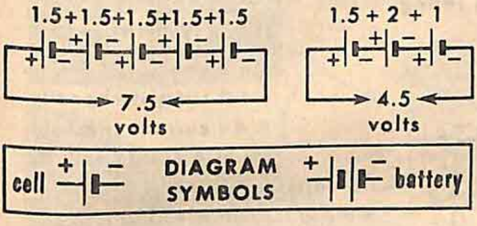

1 AMP
10 HOURS
−
+
cell
1 AMPERE x 10 HOURS = 10 AMPERE - HOURS
2 HOURS
5 AMPS
cell
5 AMPERES x 2 HOURS = 10 AMPERE - HOURS
1 HOUR
10 AMPS
cell
10 AMPERES x 1 HOUR = 10 AMPERE - HOURS

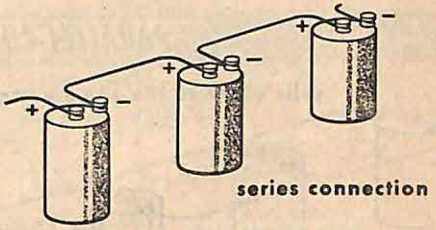
it is a measure of the useful life of a cell before recharge is necessary

Connecting Cells in Series to Form a Battery

Under certain circumstances, the voltage available from a single cell may be sufficient, as in some small flashlights. Under other circumstances, higher values of voltage may be required. This can be achieved by connecting as many cells (primary or secondary) in series as are needed to achieve the necessary voltage. Such a bank of cells forms a battery.

THE OUTPUT VOLTAGE OF CELLS CONNECTED IN SERIES IS EQUAL TO THE SUM OF ALL THEIR INDIVIDUAL VOLTAGES.

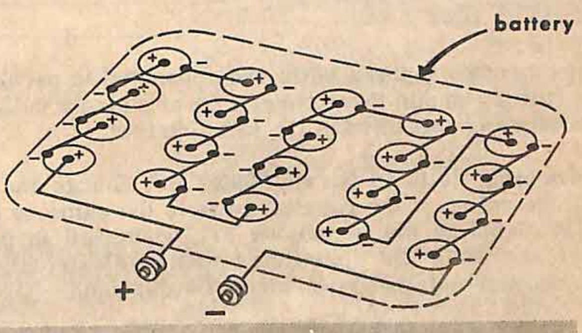




WHEN CONNECTING CELLS IN SERIES, THE POSITIVE TERMINAL OF ONE CELL IS CONNECTED TO THE NEGATIVE TERMINAL OF THE OTHER.

The total voltage of series-connected cells is the sum of the voltage output of each of the cells. Thus, if four 1.5-volt dry cells are series connected, the total voltage is 1.5 + 1.5 + 1.5 + 1.5 or 6 volts. If 30 such cells are connected in series, the output voltage is 30 x 1.5 or 45 volts. The 6-volt lead-acid storage battery consists of three 2-volt cells series connected. The 12 volt lead-acid storage battery consists of six 2-volt cells series connected.

A BATTERY IS MADE BY CONNECTING CELLS TOGETHER

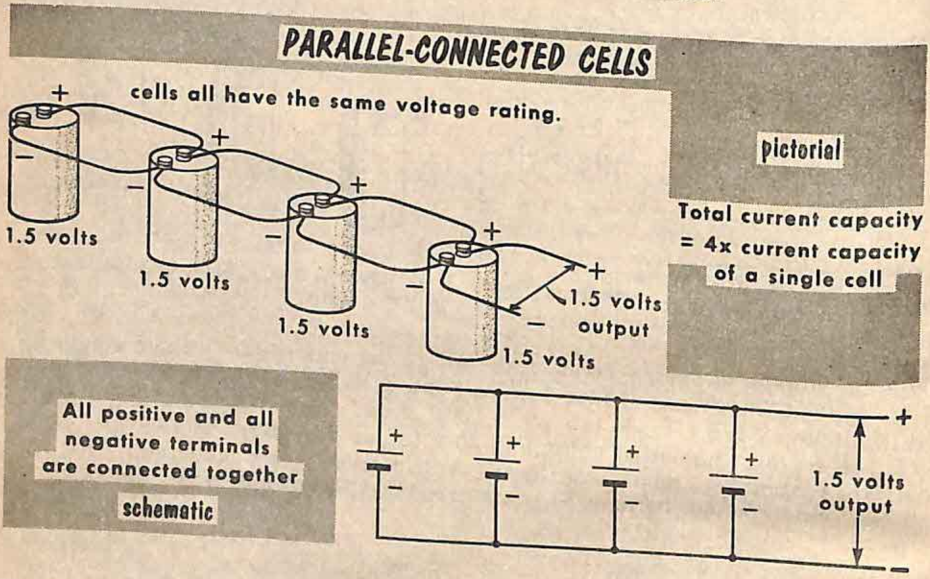


a 30 volt battery (20 1.5 Volt cells in series)

When cells are connected in series, the positive terminal of one is connected to the negative terminal of the other. By doing this, all the individual potentials or voltages aid each other, and add. The above examples involved cells rated at the same voltage. This need not be so; cells of any voltage output can be connected in series. Similarly, batteries of like or unlike voltage rating can be connected in series to increase the voltage. However, each cell (or battery) in a series arrangement should have the same current capacity.

Connecting Cells in Parallel to Form a Battery

A battery can also be formed by connecting cells in parallel. Only cells of identical output voltage rating should be connected in parallel. The purpose of a parallel connection is to increase the current capacity of the battery beyond that of a single cell. The parallel connection creates the equivalent of an increase in the physical size of the electrodes and of the amount of electrolyte, and thus increases the amount of current available.


PARALLEL-CONNECTED CELLS

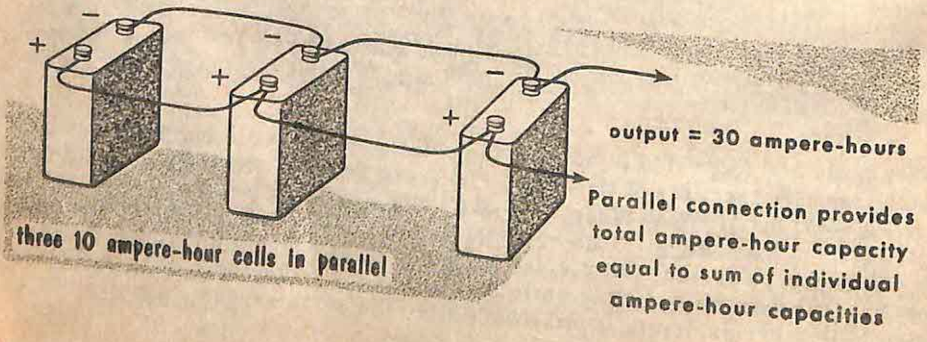
cells all have the same voltage rating.

Total current capacity = 4x current capacity of a single cell

All positive and all negative terminals are connected together

For example, if three cells are connected in parallel, the current capacity of the battery equals three times that of a single cell. Therefore, each cell is contributing one-third of the total current.

Connecting cells in parallel does not change the voltage rating. The final voltage rating of the parallel cells is the same as that of a single cell. When cells of unlike output voltage are connected in parallel, current flows between the cells and constitutes wasted electrical energy. Also, there is a possibility that the cells would be damaged.

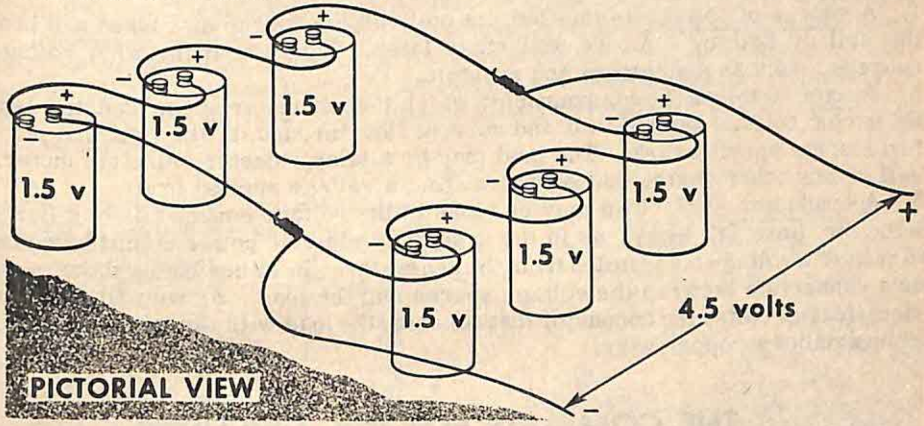

output = 30 ampere-hours

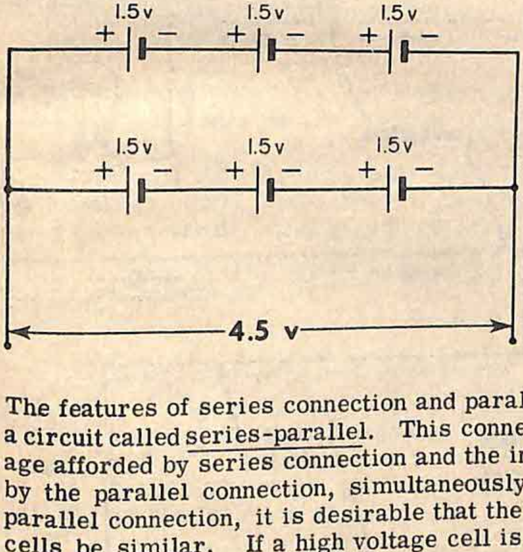
Parallel connection provides total ampere-hour capacity equal to sum of individual ampere-hour capacities

three 10 ampere-hour cells in parallel

Series-Parallel Connected Cells

THE SERIES-PARALLEL CONNECTION





SCHEMATIC DIAGRAM REPRESENTATION

Voltage is equal to that of 3 cells in series

Current capacity is equal to that of 2 cells in parallel

The features of series connection and parallel connection can be combined in a circuit called series-parallel. This connection gives the higher output voltage afforded by series connection and the increased current capacity afforded by the parallel connection, simultaneously. As in the previous examples in parallel connection, it is desirable that the current and voltage ratings of the cells be similar. If a high voltage cell is connected across a lower voltage cell, the higher voltage will cause current to flow through the lower voltage cell, possibly damaging it. Generally, this type of connection is seldom used since higher current capacity can be obtained by using larger cells. However, there may be emergency instances where the series-parallel circuit is the only practical method of obtaining the voltage and current combination desired.

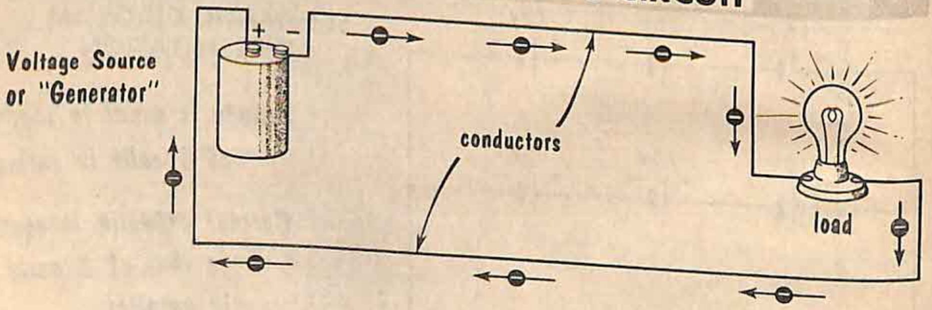
When making a series-parallel connection, the usual rules of polarity must be observed: in series circuits, connect positive to negative; in parallel circuits, connect positive to positive and negative to negative.

The Electric Circuit

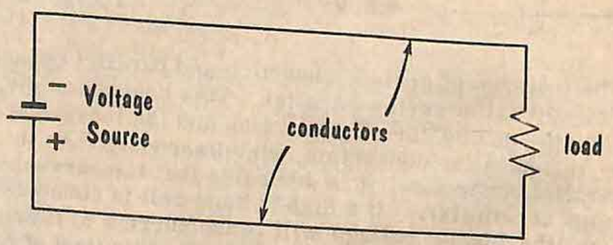
Electricity can be put to work through the use of an electric circuit. This is an organized combination of electrical components that permit some specific function to be performed. Basically, all electrical circuits consist of three main components:

1. A source of voltage -- thus far, the only voltage source discussed has been the cell or battery. As we will study later, there are many other voltage sources, such as generators and crystals.
2. A load -- this is the component for which the entire circuit is constructed. By having voltage applied to it and current flow through it, the load will perform some specific task. The load may be a lamp, toaster, electric motor, bell or any other device that operates from a voltage applied to it.
3. A conductor -- the load may be close to the voltage source, as in a flashlight, or quite far away, as in the case of an electric power company having to deliver a voltage many miles from the generator. In either case, there must be a connection between the voltage source and the load. As we will learn in electrical circuits, the conductor that connects the load with the voltage source is invariably a copper wire.

THE COMPLETE ELECTRIC CIRCUIT



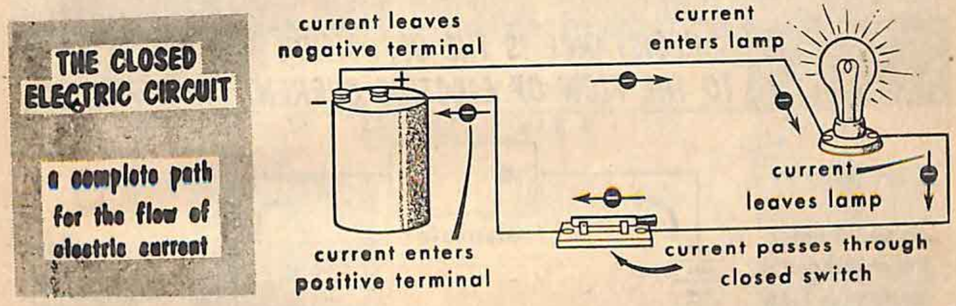
A Schematic Diagram Would Appear as...



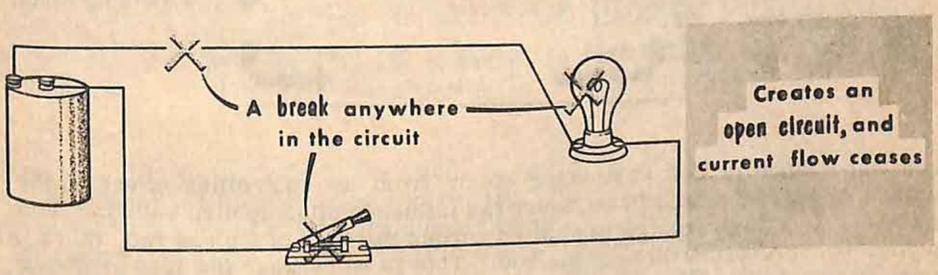
In an electric circuit, there must be a complete path for current flow. That is, there must be a conductor from the negative terminal of the voltage source to the load, and a "return" conductor from the load back to the positive side of the voltage source. Should any one of the above components be missing, we do not have an electric circuit. It is common to refer to the voltage source as the "generator" regardless of what type of voltage source is used.

The Closed Electric Circuit

Consider a very simple electric circuit consisting of a flashlight battery, a flashlight bulb, a socket for the bulb, a switch that can close or open the circuit as desired, and the wires that interconnect the elements of the circuit. We show these elements pictorially. Each of these circuit devices has two connecting points which correspond to the two openings of a piece of lead pipe. One connecting point allows the electrical energy to enter the device, the other end permits the energy to leave the device. It is to these connecting points on each device that the conducting paths (wires) are joined when forming the circuit. Each piece of conducting wire also has two connecting points, the two ends of the wire.


THE CLOSED ELECTRIC CIRCUIT
a complete path for the flow of electric current
current leaves negative terminal
current enters lamp
current leaves lamp
current passes through closed switch
current enters positive terminal
+
−

We have interconnected the elements of the circuit so that there is only one conducting path from one terminal of the battery to the switch -- from the switch to the bulb, and from the bulb to the other terminal of the battery. Let us also assume that we have depressed the movable blade of the switch so that there is an uninterrupted path through the switch for the current. We now have a closed circuit. It is considered closed because all the elements of the circuit are joined to each other and a continuous uninterrupted path exists for the flow of electric current from the battery through the devices and back to the battery.

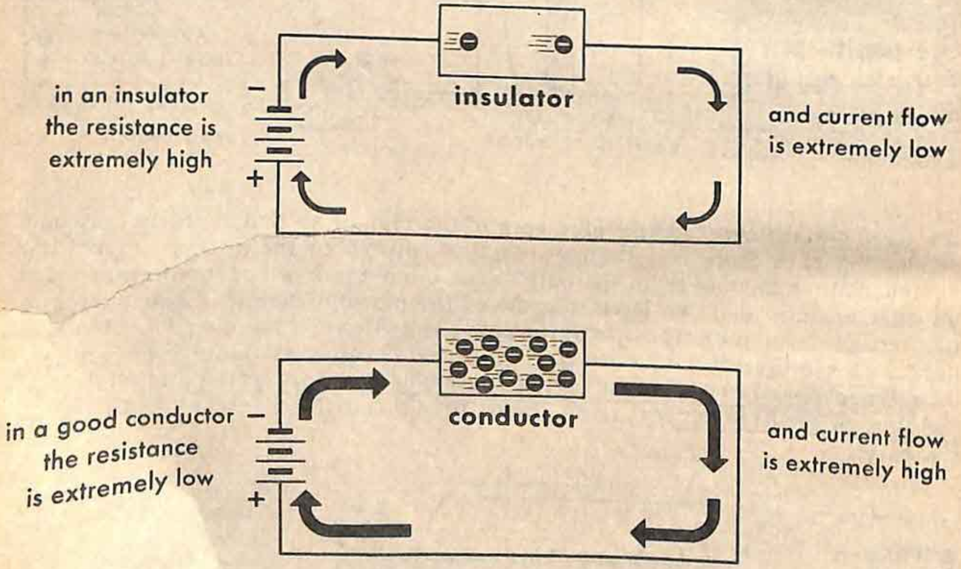

A break anywhere in the circuit
Creates an open circuit, and current flow ceases

Should this closed circuit be broken (interrupted) at any point, we have what is called an "open" circuit. The break may be unintentional, such as a broken conductor, or a burnt out filament in the lamp, or it may be intentional, such as opening the switch in order to turn off the lamp. In any case, breaking the circuit causes the current to stop flowing, and we have an open circuit.

Resistance

The word resistance as used in everyday language means opposition to an action or an idea. In the language of electricity, resistance is defined as "opposition to the flow of electric current." Now, if you will recall that electric current was described as being the directed movement of free electrons, then resistance can be looked upon as being the opposition to the motion of free electrons. From this, we can conclude that wherever free electrons are in motion, there is resistance to their movement. This is called d-c (direct current) resistance. (Direct current describes current flow in one direction. Later in this course, we will study a-c or alternating current, where current flows alternately in both directions.) If we relate this action to metals, all metals regardless of their shape or purpose, offer electrical resistance.

RESISTANCE IS THE OPPOSITION TO THE FLOW OF ELECTRIC CURRENT

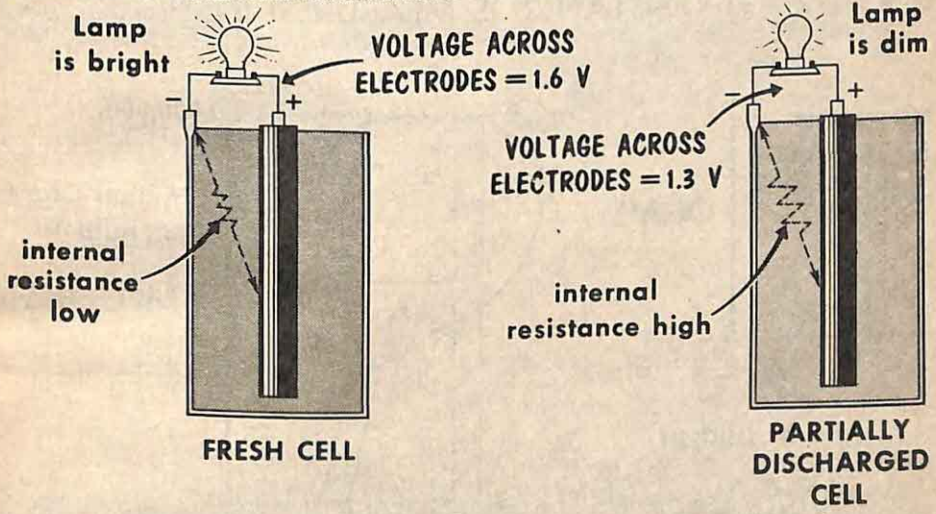

in an insulator the resistance is extremely high
−
+
insulator
and current flow is extremely low
in a good conductor the resistance is extremely low
−
+
conductor
and current flow is extremely high

The importance of d-c resistance stems from its controlling effect on the amount of current which flows under the influence of an applied voltage. For instance, if a high voltage is applied across the ends of a glass rod, there is negligible current flow through the rod. This is so because few free electrons exist in the glass. Glass is called an insulator because it has few free electrons to perform as electric current; an insulator does not conduct electricity well. If, now, we interpret poor conductivity due to insufficient free electrons as being the equivalent of very high d-c resistance, we have still another basis of d-c resistance. So, although several different conditions underlie d-c resistance, the end result is the same -- a limitation on the amount of current flow.

D-C Resistance of Voltage Sources (Internal Resistance)

The chemical action inside primary and secondary cells involves the movement of electricity through the electrolyte in which the active electrodes are immersed. In both the dry and the wet cell, the electricity in motion within the cell is in the form of positive and negative ions -- atoms shy electrons and atoms with excess electrons. The generation of voltage is accounted for in part by the decomposition of the electrodes, as well as by a change in the makeup of the materials as the two kinds of ions enter or leave the electrodes. It is this action which ultimately leads to the supply of free electrons from the negative terminal.

CELLS HAVE INTERNAL RESISTANCE

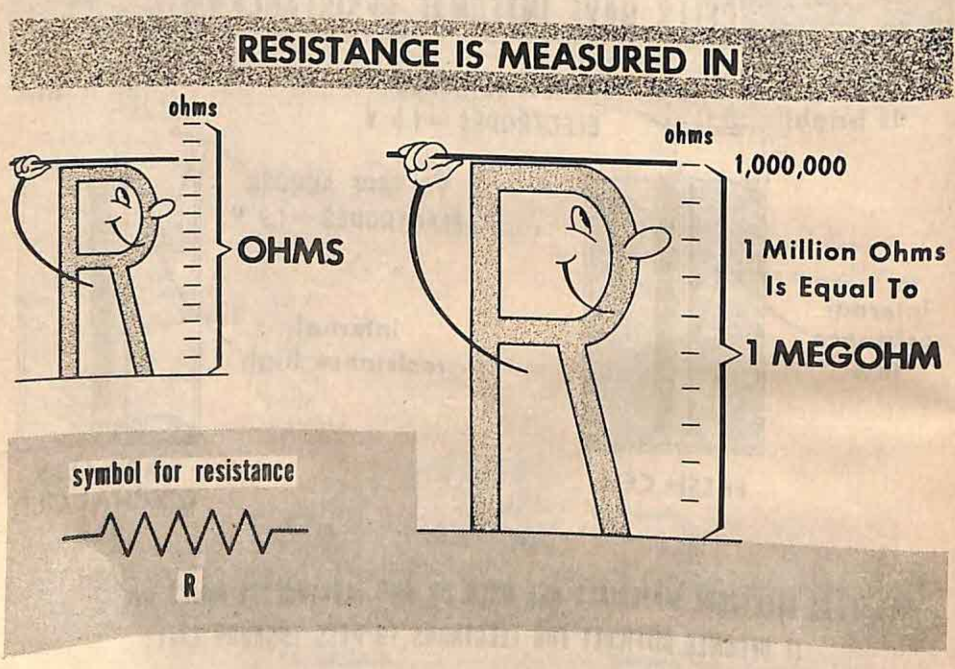

Lamp is bright
VOLTAGE ACROSS ELECTRODES = 1.6 V
−
+
internal resistance low
FRESH CELL
Lamp is dim
−
+
VOLTAGE ACROSS ELECTRODES = 1.3 V
internal resistance high
PARTIALLY DISCHARGED CELL

AS ELECTRODE MATERIALS ARE USED UP AND ELECTROLYTE DRIES UP, IT BECOMES DIFFICULT FOR ELECTRONS TO PASS THROUGH CELL

However, the conversion of chemical energy into electrical energy does not occur with 100% efficiency; some waste usually takes place. We attribute the loss to the presence of resistance inside the cell -- resistance that is inseparably associated with the action. It is called internal resistance. It is least when the chemicals are fresh and the action is strong. As the cells function and discharge, the internal resistance gradually increases, becoming higher when the cell is discharged. In the secondary cell, the internal resistance is high when the battery is discharged but reduces to its normally-low value as the battery is recharged. When cells are part of an electrical system and are supplying the circuit current, the internal resistance of each cell of the battery is considered as being in the path of the circuit current.

Unit of Resistance (The Ohm)

D-c resistance is indicated by the capital letter R and, when symbolized, it appears as a zigzag line. Because the amount of resistance presented to current flow is not always the same and it is necessary to express and compare different amounts of resistance, science has established a unit of resistance. It is the ohm. The origin of the word ohm is the name George Simon Ohm. He was a German scientist who advanced the concept that a definite relationship existed between the amount of current flow, the amount of voltage applied, and the resistance of the electrical system. The concept defined the unit ohm as being that amount of resistance which limits current to 1 ampere when the applied voltage is 1 volt.



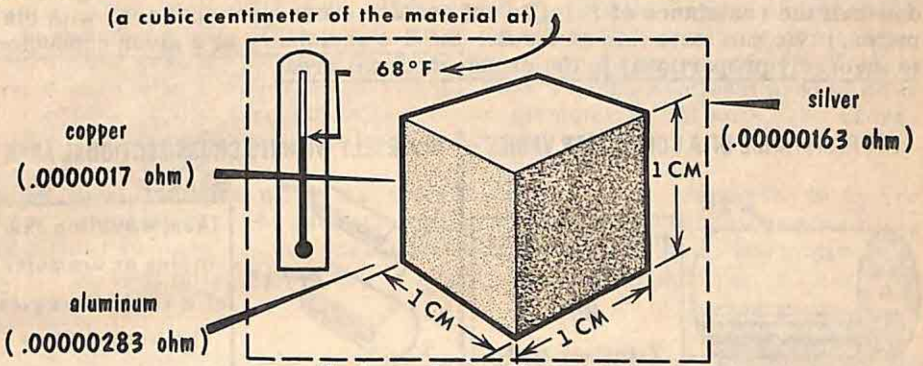
Practical amounts of resistance encountered in radio circuits range from a fraction of 1 ohm to several million ohms. As a matter of convenience, the words "milli" meaning one-thousandth, "kilo" meaning thousand, "meg" meaning one million, and "micro" meaning one-millionth are used in connection with resistance. Thus, .001 ohm is 1 milliohm, 1000 ohms is 1 kilohm, 1,000,000 ohms is one megohm, and 1 micro-ohm is 1/1,000,000 or .000001 ohm. You will recall these words being used in connection with voltage and current values. In addition to prefixes being used to express values of resistance, several letter symbols indicate resistance.

OMEGA Ω	=ohms	100 Ω	=100 ohms
KILO or K	=1000	4 K	=4000 ohms
MEG or M	=million	5 MEG	=5,000,000 ohms

Factors That Determine Resistance in Metals (Material and Length)

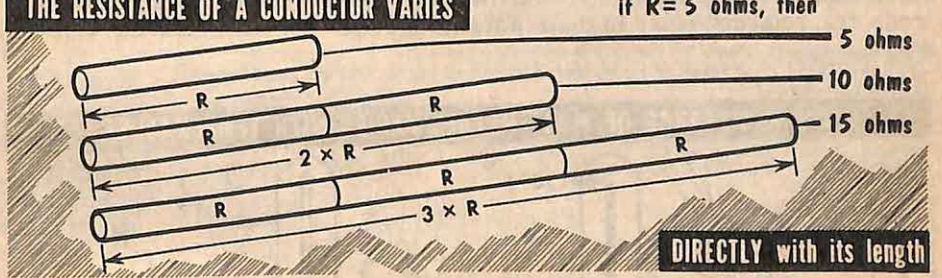
Several physical features of conductors determine the amount of resistance they present to the flow of current. They are: (1) kind of material; (2) length; (3) cross-section; (4) temperature.

Resistance Of A Material Is Measured By Its SPECIFIC RESISTANCE...



...the lower the specific resistance the better the conductor

A basis for comparing the usefulness of metals as conductors of electricity is by specific resistance. This is the ohmic value of a standard amount (1 cubic centimeter) of the substance measured at a particular temperature (68° F). If the specific resistance of a substance is high, it is a "high-resistance" material; if the specific resistance is low, it is a "low-resistance" material. The lower the specific resistance, the better the material performs as a conductor of electric current.

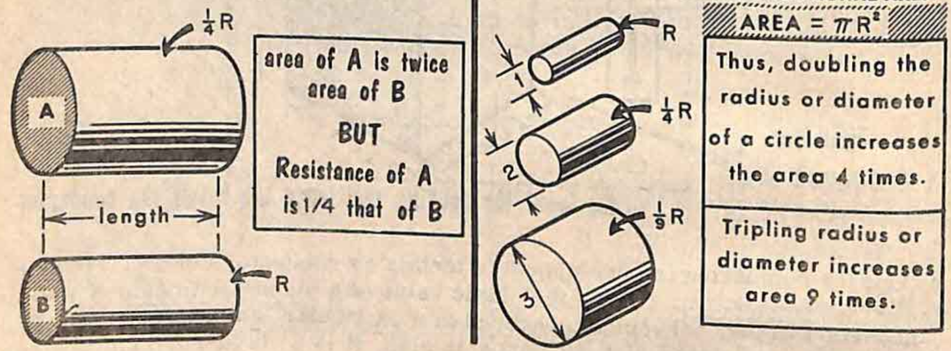


Given any one particular conductor material having a specific resistance, the longer the conductor, the more will be its resistance. If, for instance, the conductor is pure copper and a piece 1 foot long and 3/8 inch in diameter has a resistance of .00005 ohm, a piece 100 feet long will have a resistance 100 times as great or .00005 x 100 or .005 ohm. Each foot of length contributes its share of resistance to the total. This leads to the basic rule: the resistance of a conductor is directly proportional to its length .

Factors That Determine Resistance in Metals (Cross Section and Temperature)

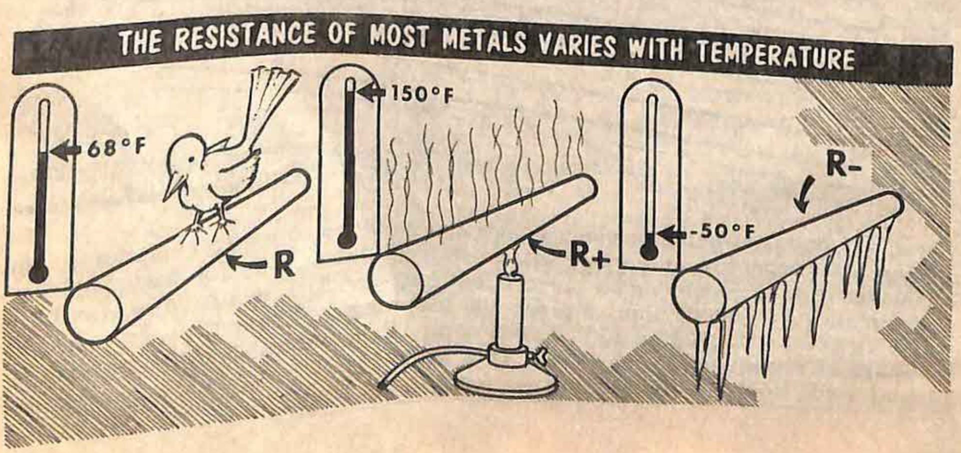
The "thickness" or cross section of a wire made of a given material has a great effect on its resistance. The greater the cross section of a conductor (the thicker the wire), the less its resistance per unit length -- the reason being that the greater the cross section, the more numerous the free electrons to be moved by a given applied voltage. Given two equal lengths of the same wire A and B, with A having twice the cross-sectional area of B, wire A will present one-half the resistance of B. (Do not confuse cross-sectional area with diameter.) We can state this as a rule: the d-c resistance of a given conductor is inversely proportional to the cross-sectional area.

THE RESISTANCE OF A CONDUCTOR VARIES INVERSELY WITH ITS CROSS-SECTIONAL AREA


$\frac{1}{4}$R
A
length
B
R
area of A is twice area of B
BUT
Resistance of A is 1/4 that of B
R
1
$\frac{1}{4}$R
2
$\frac{1}{9}$R
3
AREA = πR^2
Thus, doubling the radius or diameter of a circle increases the area 4 times.
Tripling radius or diameter increases area 9 times.

The higher the temperature of ordinary metal conductors, the higher the resistance per unit length and cross section. The reason for this is simply that an increase in temperature causes more violent motion of the free electrons and atoms inside the wire, thus increasing the number of collisions between electrons, and between electrons and atoms. The result is that the free electrons are retarded more in their advance through hot wire than through cold wire.

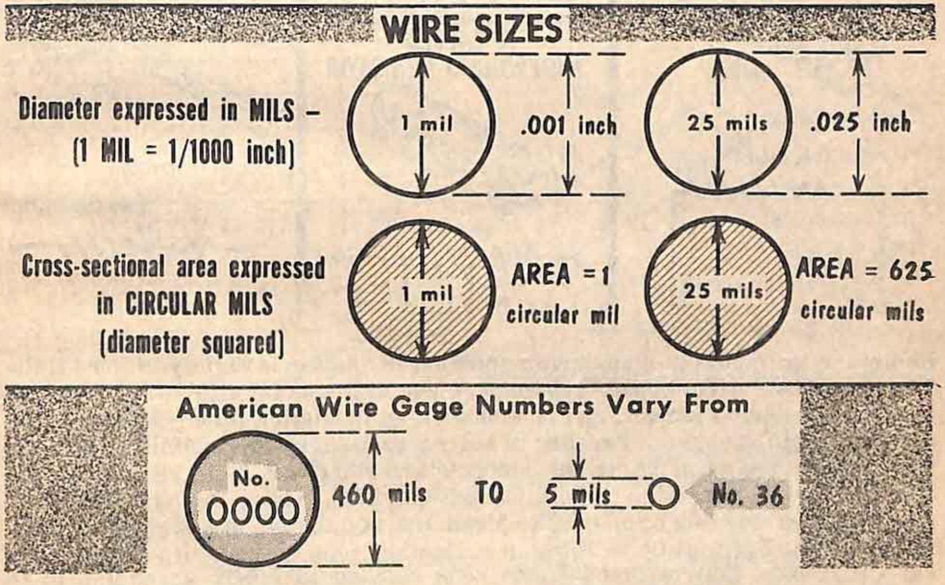
THE RESISTANCE OF MOST METALS VARIES WITH TEMPERATURE



Practical Units of Wire Sizes — American Wire Gage

It is standard American practice to use different units to express length and cross-sectional area. Length can be expressed in a variety of units--inches, feet, or miles (depending on the circumstances). Units of 1000 feet are commonly used. To express cross-sectional area, it is customary to use circular mils, in which case, the diameter is stated in terms of the mil. A mil equals 1/1000 inch (.001 inch). One circular mil is the area of a circle with a diameter of 1 mil. This follows from the formula for the area of a circle, which is the area proportional to the square of the diameter, or d^2. Thus, a round wire with a diameter of 100 mils has a cross-sectional area of d^2 or 100 x 100 = 10,000 circular mils. If the diameter is 400 mils, the cross-sectional area is 400 x 400 or 160,000 circular mils.

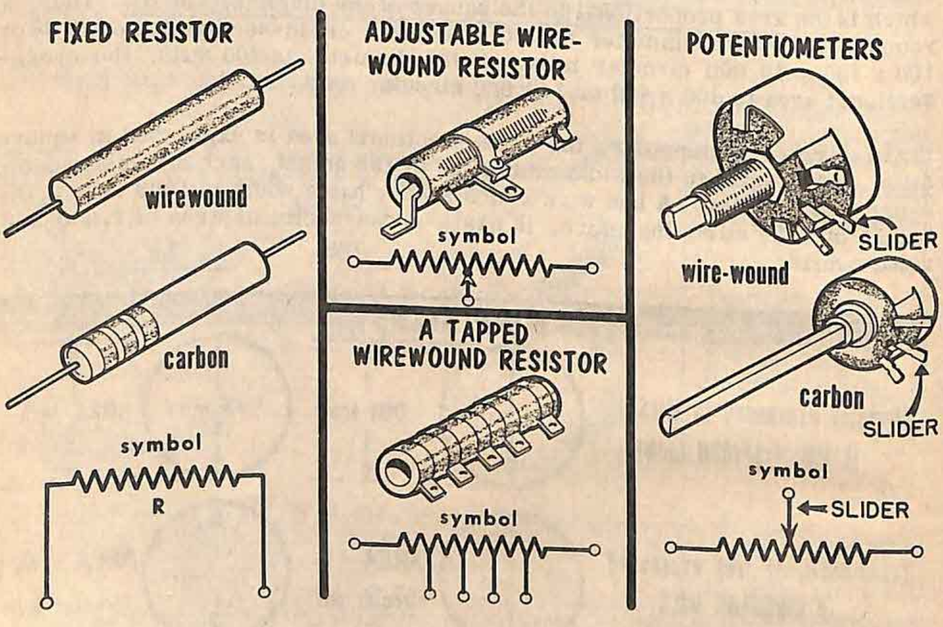
If the wire is rectangular, the cross-sectional area is expressed in square mils, and is equal to the width multiplied by the height, each dimension being expressed in mils. A bus wire 1 inch square has a width of 1000 mils and a height of 1000 mils; therefore, it has a cross-sectional area of 1,000,000 square mils.



Wire sizes are listed by gage numbers, diameters in mils, cross-sectional areas in circular mils, resistance in ohms per thousand feet, and weight in pounds of conductor material per thousand feet. Although there are many types of gages, the most frequently used is the American Wire Gage (AWG), formerly called the Brown and Sharpe (B & S) Gage. The AWG is so constructed that the ratio of any one diameter to the next in order is constant. The largest size, No. 0000 or 4/0, has an arbitrary diameter of 460 mils and the smallest, No. 36, a diameter of 5 mils. Between these two sizes there are 39 other sizes. A wire table of the AWG is given in the Appendix.

Resistors

The manufactured version of resistance is the resistor. A resistor is an electrical component which, when made part of an electrical circuit, is intended to introduce a definite amount of d-c resistance in very compact form. In many applications, the purpose of the added resistance is to limit the amount of circuit current to a predetermined value. As we will learn, there are other functions as well.



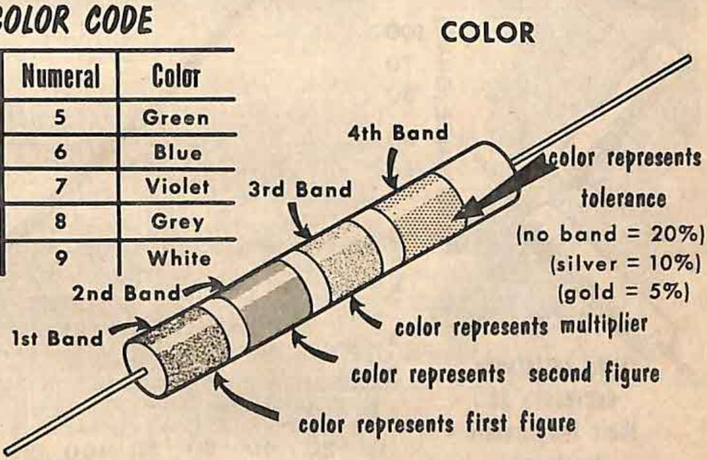
Resistors are made in many sizes and shapes, and in a variety of materials. The so-called "wire-wound" type makes use of a special alloy wire or ribbon as the resistance element, and is wound on an insulating form, with or without a ceramic covering. Because of the current carrying capabilities of wire, this type is used when the circuit currents are relatively high. They are available in fixed, adjustable, or continuously-variable types. Resistance values range from a fraction of an ohm to about 100,000 ohms, in power (wattage) ratings from 1/2 watt up to 200 watts. Another type is made of graphite or carbon powder that is formed into rods and cut to length according to the resistance desired. They are fixed in their ohmic value and in their power-handling capabilities. Another type of fixed resistor consists of a thin film of metal deposited on an insulating form. Both the carbon and the deposited-metal types are low-current units and are availabe in resistance values from several ohms to as high as 50,000,000 ohms (50 megohms); and in wattage ratings from 1/4 watt to 2 watts. Connection to the wire resistor is by means of terminals. Carbon and deposited-metal types are connected by means of wire leads called pigtails. Continuously-variable resistors (potentiometers) provide any amount of resistance to the maximum. A rheostat is a kind of variable resistor designed to handle large amounts of current.

Resistor Ratings and Color Codes

The usefulness of a resistor is measured by its electrical rating. There are three factors used to determine this rating: the ohmic value; the heat dissipating capability; and the resistance tolerance. The tolerance of a resistor is the permitted variation in percent from its rated ohmic value. The heat dissipating capability is also known by another name -- wattage rating -- which we shall learn in detail later. The ohmic value cannot be recognized by merely looking at the resistor; hence, the resistor is labeled in some way. Fixed, adjustable, or variable wirewound resistors often have their values stamped right on them. In the case of fixed carbon and deposited-metal resistors, a color code consisting of three or four colored bands or dots is used. The color code indicates both ohmic value and resistance tolerance. To "read" the code correctly, the resistor must be held in such a position that the colored bands or dots appear at the left, and the value is then read from left to right. The length and thickness of the resistor is an indication of its wattage rating. If no tolerance indication is given, a tolerance of 20% can then be assumed.

RESISTOR COLOR CODE

Numeral	Color	Numeral	Color
0	Black	5	Green
1	Brown	6	Blue
2	Red	7	Violet
3	Orange	8	Grey
4	Yellow	9	White


COLOR
4th Band
color represents tolerance
(no band = 20%)
(silver = 10%)
(gold = 5%)
3rd Band
2nd Band
1st Band
color represents multiplier
color represents second figure
color represents first figure

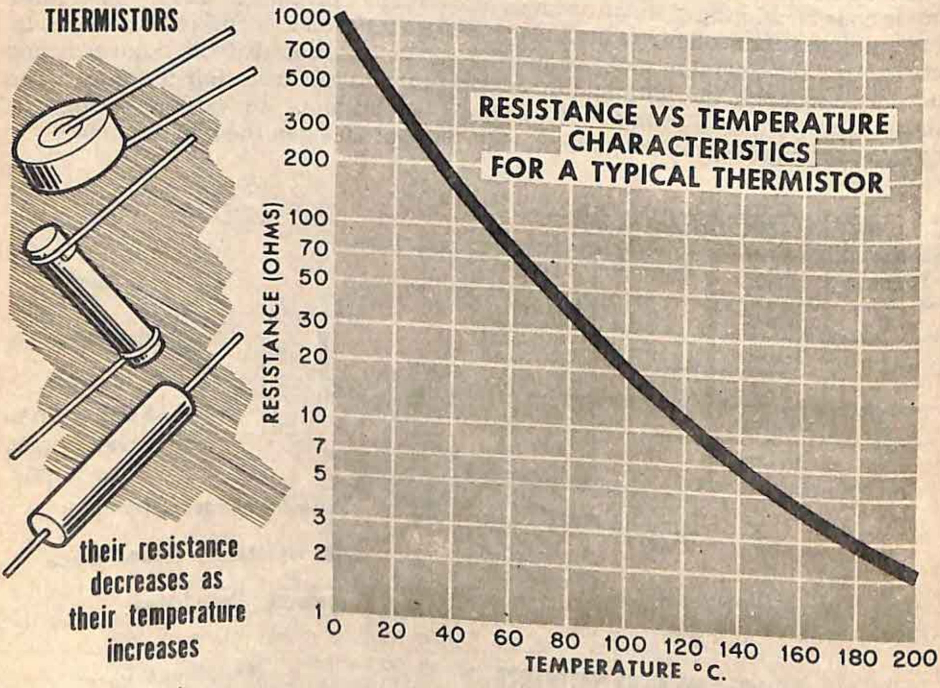
RESISTOR TOLERANCE

If Tolerance is:	Resistance may be anywhere from:
20%	80 ohms to 120 ohms
10%	90 ohms to 110 ohms
5%	95 ohms to 105 ohms
1%	99 ohms to 101 ohms

Assume a fixed carbon resistor that is color-coded yellow, violet, orange and silver. It would read "four, seven, three zeros, and 10%," meaning 47,000 ohms rating with a resistance tolerance of plus or minus(±) 10%. An earlier code now obsolete consisted of a body color, an end color and a dot. The body color represented the first significant figure, the end color represented the second significant figure, and the dot represented the number of zeros.

Special Resistors

Sometimes, it is necessary to use resistors having special characteristics or functions. Such a unit is the ballast resistor. This is a resistor whose resistance increases as the amount of current flowing through it increases, or as its temperature increases. While this characteristic is true of all conventional resistors, the ballast resistor is placed in certain circuits for the sole purpose of maintaining a high resistance while current flow is high, and to exhibit a lower resistance when the current flow is low. In some instances, it is used to provide nothing more than a "voltage drop" in a circuit.



Another special resistor is the thermistor. Unlike conventional resistors whose resistances increase as their temperatures increase, the thermistor exhibits the opposite properties -- its resistance decreases when its temperature increases (has a negative-temperature coefficient). Thus, an increase in current flow through a thermistor would cause its temperature to increase and its resistance to decrease. As we will see, this property of the thermistor is used in special "temperature-compensating" circuits.

The third special resistor is the voltage-sensitive varistor. The varistor exhibits a significant and non-linear change of resistance with applied voltage. An increase in the applied voltage causes an increase in current which is much higher than is the case with a standard resistor. Because of the change of resistance with voltage, no resistance rating is listed regarding varistors. Instead, a voltage is listed for a specified current.

The unit of quantity for electric current is the coulomb; a coulomb per second is defined as an ampere.

Electric current has three effects: heat; magnetic; and chemical.

Resistance is the opposition to the flow of electric current.

Electrical circuits consist of a source of voltage, a load, and a conductor.

The resistance of any material depends on its length, cross-section, and temperature.

A primary cell is not rechargeable and has a limited life; a secondary cell is rechargeable and has a longer life.

Dry cells are rated in ampere-hours at a specified rate of current flow.

The most commonly-used primary cell is the zinc-carbon type.

The most widely-used secondary cell is the lead-acid "storage" type.

The lead-acid cell can be recharged by reversing the direction of the discharge current.

Batteries should be tested "under load" (while discharging).

The current capacity rating for storage batteries is usually based on a steady 20-hour discharge. A 100 ampere-hour lead-acid battery will furnish 5 amperes for 20 hours.

A hydrometer is used to measure the specific gravity of the electrolyte in a lead-acid cell, which is a good indication of the charge condition of the battery.

When cells are connected in series, the positive terminal of one is connected to the negative terminal of the other.

Connecting cells in series increases the voltage available.

Connecting cells in parallel increases the current capacity of a battery.

Series-parallel connected cells give both higher voltage output and increased current capacity.

Active material refers to the spongy lead and lead peroxide which are pressed into the grids of the plates of a lead-acid cell.

The ohm is the unit of electrical resistance; a resistor is the component which offers this resistance.

The usefulness of a resistor is determined by its electrical rating.

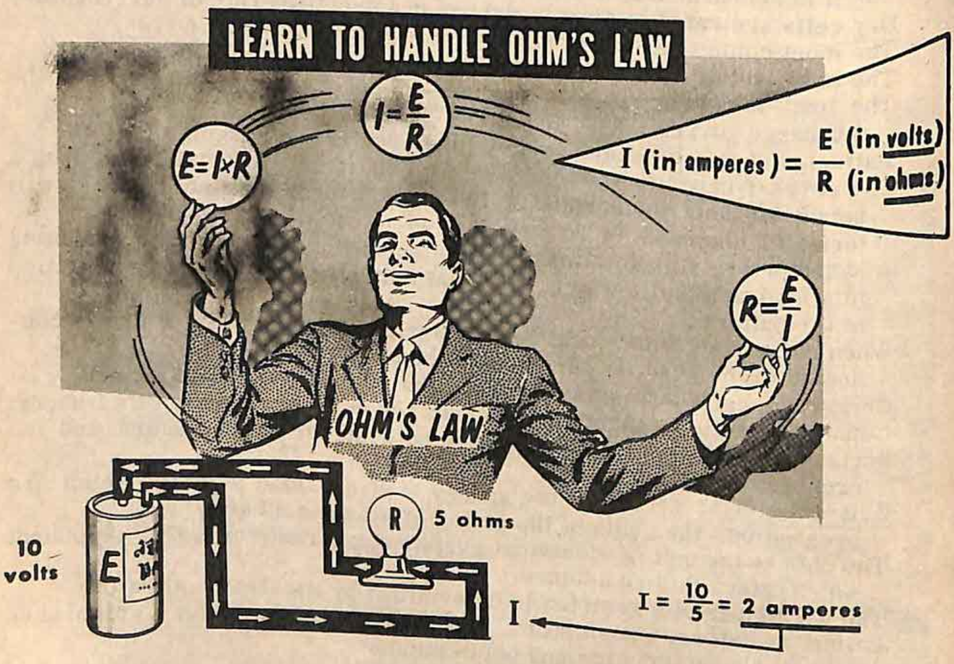
Ballast resistors, thermistors, and varistors are resistors which have special characteristics and applications.

REVIEW QUESTIONS

1. What is the unit of measurement for resistance? For electric current? For electromotive force?
2. Name three types of resistors having special characteristics and applications. What are these characteristics?
3. Define resistance. What physical factors influence resistance?
4. What colors are used to indicate a resistance of 4700 ohms, 10% tolerance?
5. How are dry cells rated?
6. Electrical circuits consist of three main components. What are they?
7. What is the difference between a primary cell and a secondary cell?
8. Upon what does the voltage of a primary cell depend?
9. How should batteries be properly tested?
10. How does connecting cells in parallel affect the current capacity of a battery?
11. What method of combining cells gives both increased current capacity and higher output voltage?

Ohm's Law for Finding Current

Applying a voltage to a circuit causes current flow; the presence of resistance opposes the flow of current. How can we reconcile the seemingly opposite actions of voltage and resistance? George Simon Ohm, a German scientist, investigated the behavior of electric current more than 100 years ago and summed it up in a single, simple formula called Ohm's law. This law, in its various forms, is one of the foundations on which the study of electricity rests.

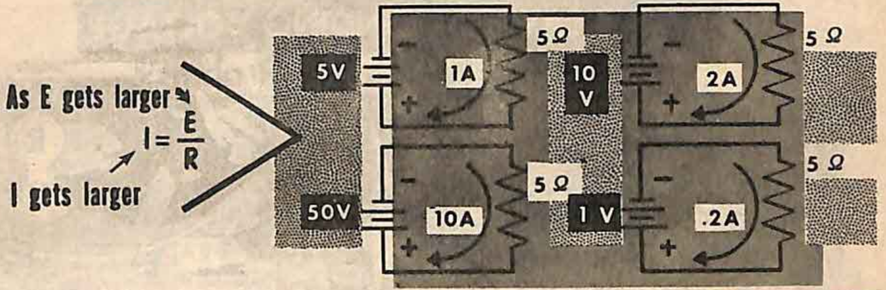

LEARN TO HANDLE OHM'S LAW
$I=\frac{E}{R}$
$E=I\times R$
I (in amperes) = E (in volts) / R (in ohms)
$R=\frac{E}{I}$
OHM'S LAW
R
5 ohms
10 volts
E
I
$I=\frac{10}{5}=$ 2 amperes

Let us examine the formula by studying its application to a very simple d-c circuit. The battery supplies a voltage we call E to a flashlight bulb filament whose operating resistance we call R. We neglect the resistance of the circuit-connecting wire, the internal resistance of the battery, and the resistance of the switch. When the switch closes the circuit, current flows. But how much current? To answer the question, we must know the values for E and R, or how much voltage is pushing and how much resistance is opposing the current. So we shall say that E = 1.5 volts and R = 3 ohms. Then I = 1.5/3 or .5 ampere, which also equals 500 milliamperes. Let's try another set of values. Suppose that E = 3 volts (or twice as much as before) but R is 3 ohms (the same as before). How much current would flow in the circuit? Substituting the numbers in the equation, I = 3/3, or 1 ampere. Doubling the voltage doubled the current. The significant fact to remember here is that the current varies directly with the applied voltage when the resistance remains constant. This is one of the basic relationships between current and voltage when resistance is kept constant. The same relationship would hold true if the voltage were reduced while the resistance remained constant.

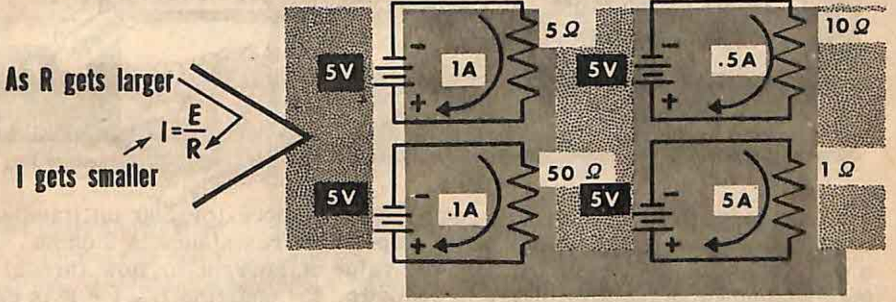
Ohm's Law (Cont'd)

We have seen that current varies directly with voltage when resistance is constant, but what happens to the current when the resistance varies? Since current is still the unknown quantity, we work with the same equation (I = E/R).

CURRENT VARIES DIRECTLY WITH VOLTAGE



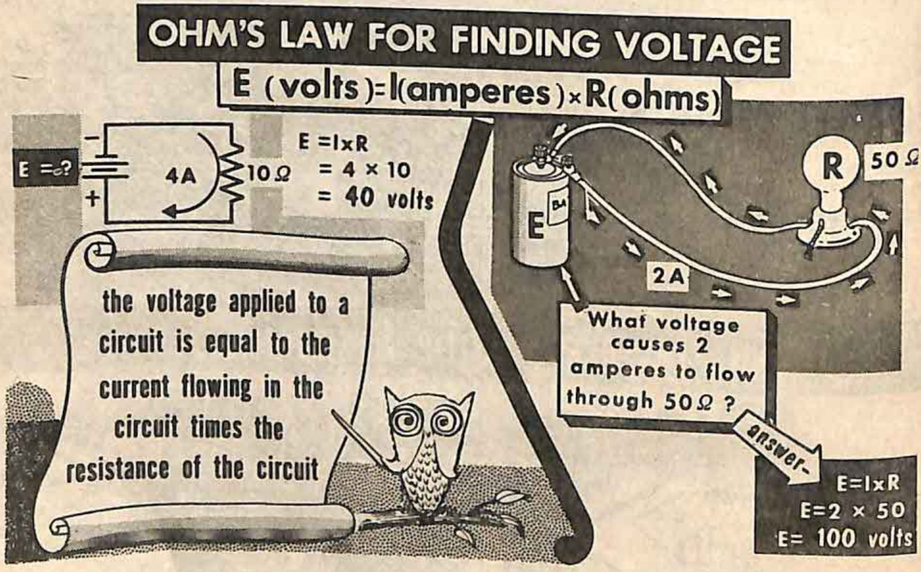
AND INVERSELY WITH RESISTANCE.



Assume that E = 1.5 volts, but now, we shall substitute a different filament for R. Now the operating resistance is 10 ohms. How much current will flow in the circuit? I = 1.5/10 = .15 ampere (or 150 milliamperes). It is readily evident that with the voltage constant, any increase in resistance reduces the current. In fact, we can be specific and say that current varies inversely with resistance. Let's hold E at 1.5 volts and now assume that R is 30 ohms, or three times the value used before. Now I = 1.5/30 or .05 ampere (or 50 milliamperes). Thus, the resistance was increased three-fold and the current decreased to one-third its previous value. In other words, when the voltage is held constant, the current varies inversely with the resistance. This too is a basic relationship. Make another computation with E = 1.5 volts and R = 5 ohms. Your answer is .3 ampere (or 300 milliamperes). It shows that decreasing resistance increases the current -- always inversely -- with the change in resistance.

Ohm's Law for Finding Voltage

There is still another form of Ohm's law. It enables the determination of the voltage E when the current I and the resistance R are known. This equation is a tool for determining the answer to two possible questions that are frequently encountered in electrical circuits. One is: What value of voltage causes the flow of a known current I through a known resistance R? The other is: How much voltage must be applied in order for a given current I to flow through a known resistance R?

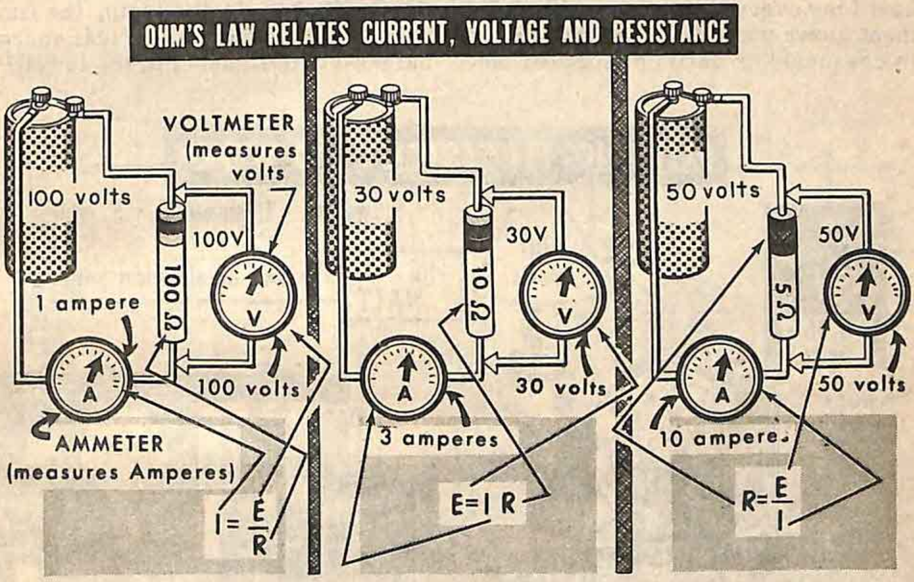

OHM'S LAW FOR FINDING VOLTAGE
E (volts)=I(amperes)×R(ohms)
E =?
4A
10Ω
+
E =I×R
= 4 × 10
= 40 volts
the voltage applied to a circuit is equal to the current flowing in the circuit times the resistance of the circuit
E
R
50Ω
2A
What voltage causes 2 amperes to flow through 50Ω ?
answer-
E=I×R
E=2 × 50
E= 100 volts

For instance, a flashlight bulb requires .5 ampere (or 500 milliamperes) current for proper operation, and its operating resistance is 3 ohms. How much voltage must be applied for this value of current to flow through the bulb filament? Since the voltage is unknown, the equation E = I × R is used. Substituting the known electrical quantities for the letters, we have E = .5 × 3 = 1.5, or E = 1.5 volts. Let's consider another case. A different flashlight bulb is used. This one is rated at .5 ampere current (I) flow but its operating resistance (R) is 30 ohms. How much voltage must be applied so that the filament will glow with the proper intensity? Now E = .5 × 30 = 15, or E = 15 volts. With the current kept constant, an increase in resistance requires an increase in applied voltage. In other words, the change in required voltage varies directly with the change in resistance.

If you will examine the equation for voltage (E) closely, you will note that E is the product of two quantities, I and R. If either of these quantities remains constant, the voltage E changes in direct proportion to the change in the other quantity. Suppose I = .25 ampere and R = 3 ohms. The voltage then equals .25 × 3 or .75 volts. Compare this with the first problem on this page. Note that halving the current reduced the required voltage exactly in half.

Ohm's Law for Finding Resistance

There is still another important form of the basic Ohm's Law. It is used when the resistance R is the unknown quantity and current I and voltage E are known. This formula is used to determine the amount of resistance that is present in a circuit when a given amount of current is being driven through a circuit by a known amount of voltage. It is also used to determine the value of resistance required to limit the current to a known value when a voltage of a known value is applied.



OHM'S LAW RELATES CURRENT, VOLTAGE AND RESISTANCE

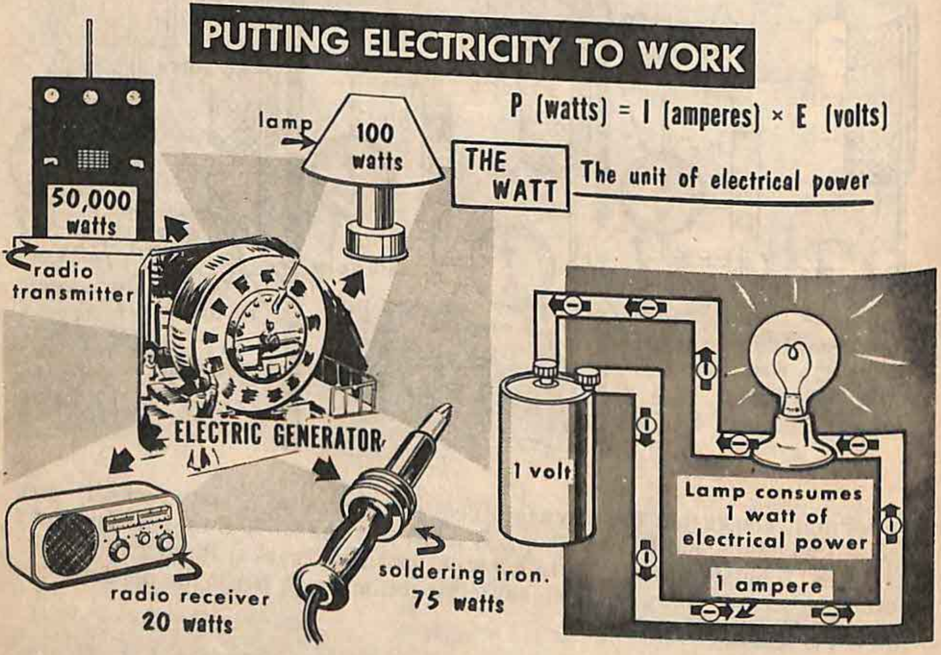
The formula shows that R varies in direct proportion to E and inversely with I. If E increases and I is constant, R must increase. If E is constant and I increases, R must be less; if E is constant and I decreases, R must increase. In other words, R changes in the same direction as E, but in the opposite direction to I.

Assume E to be 3 volts and the flashlight bulb filament to be rated at .15 ampere. What is the operating resistance of the filament? Solving for $R = 3/.15 = 20$ ohms. Consider this case: E remains at 3 volts, but now we use a bulb whose filament requires .3 ampere for proper operation. What is its resistance? Solving $R = 3/.3 = 10$ ohms. Note that with the voltage constant, doubling the current required a reduction of the resistance to one-half the original value. This is the inverse proportion relationship. Let's double the voltage and keep the current constant at .3 ampere. Then $R = 6/.3 = 20$ ohms. Doubling the voltage with the current constant required a two-fold increase in resistance. This is the direct proportion relationship.

Try solving this problem: E = 150 volts and I = 20 milliamperes (20 milliamperes = .02 ampere). What is the value of R? Is your answer 7500 ohms?

Electrical Power and the Watt

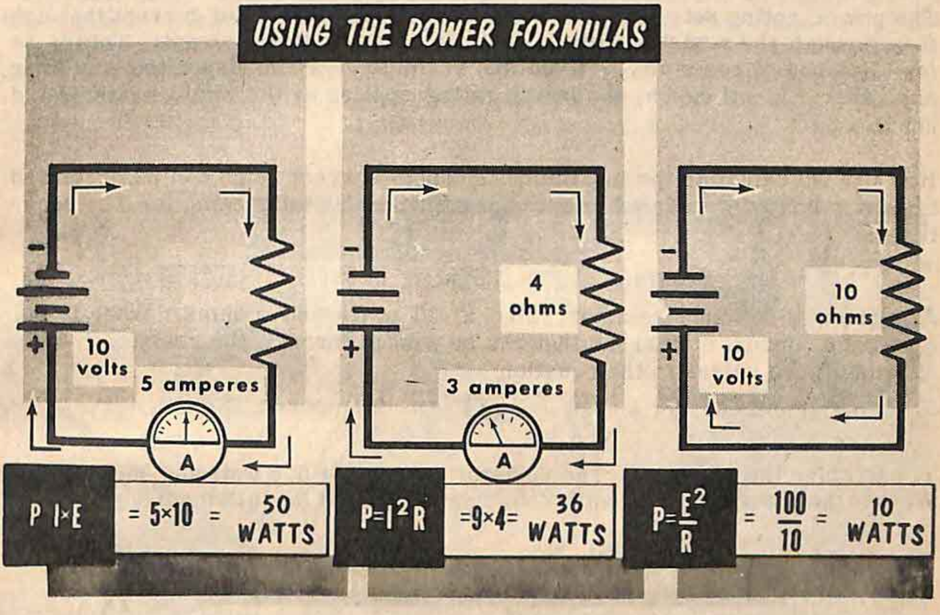
When a voltage forces current to flow through a resistance, it does so against the opposition of the resistance. Overcoming the resistance of the circuit uses up electrical energy. We can compare this to pushing a large box across the floor. In this case, the opposition is the friction of the floor to the box. This friction causes a certain amount of heat to be produced, with the heat representing a loss, or wasted energy. In a simple electrical circuit containing a battery, conductor, lamp, and switch, there will be an electrical loss in the form of heat throughout the circuit. For all practical purposes, however, the heat loss everywhere but in the lamp is insignificant. In the lamp, the filament glows white hot, and radiates light. The rate at which electrical energy is consumed or used up is called electrical power, designated by the letter P.


PUTTING ELECTRICITY TO WORK
P (watts) = I (amperes) × E (volts)
THE WATT
The unit of electrical power
lamp
100 watts
50,000 watts
radio transmitter
ELECTRIC GENERATOR
radio receiver
20 watts
soldering iron.
75 watts
1 volt
Lamp consumes 1 watt of electrical power
1 ampere

The unit used to express electrical power is the watt, named after James Watt, the inventor of the steam engine. Using our electrical standards, we can say that 1 watt of electrical energy is used up forcing 1 ampere of current through a circuit under the influence of 1 volt. It is important to remember that power represents the rate of doing work, and not the amount of work done. A man can do as much work as a steamshovel, but in far more time -- hence, a man has far less power. Electrical power is equal to the amount of current in a circuit times the voltage applied to the circuit ($P = I \times E$), and is measured in watts. To compare electrical to mechanical power, we use the figure 746 watts (electrical horsepower). This amount of electrical power will do as much work as a mechanical device capable of performing 550 foot-pounds of work per second (1 mechanical horsepower).

Power Formulas

Being able to determine the power conditions in an electrical system is very important. It underlies the selection of the correct component to do a job, as well as recognizing if the operating conditions are right or wrong. Three related equations enable the calculation of electrical power (P) in watts. Each has a particular application, depending on which two of the three quantities -- volts (E), current (I) and resistance (R) -- are known. Under any circumstances, either E and I, I and R, or E and R must be known.



Let's solve some power problems using the battery and the flashlight bulb. Assume that E is 1.5 volts and the bulb filament requires .5 ampere (therefore I is .5 ampere). The applicable equation is $P = E \times I$. Using numbers instead of the letters, $P = 1.5 \times .5 = .75$ watt or 750 milliwatts.

Suppose we do not know the voltage, but we do know that the filament current is .5 ampere and the operating resistance is 3 ohms. Then $P = I^2 \times R$ or $(.5 \times .5) \times 3 = .25 \times 3 = .75$ watt.

As a third case, assume that we know the voltage to be 1.5 volts and the resistance to be 3 ohms. We do not know the current. The applicable formula is $P = E^2/R$ or $P = (1.5 \times 1.5)/3 = 2.25/3 = .75$ watt.

Using the above examples of power formulas, try solving the power for the following conditions: $E = 120$ volts, $I = 10$ amperes and $R = 12$ ohms. Use each of the three formulas, using only those quantities which apply. Is your answer 1200 watts? (1200 watts = 1.2 kilowatts). It should be!

Power Rating of Resistors

All electrical devices and circuits bear some association to electrical power ratings, but resistors in electrical and communication equipment are most prominent in this connection. The wide variety of resistors have many kinds of uses, the foremost of which is the control of current. A prime requirement, therefore, of all resistors, is the ability to dissipate the electrical energy delivered to them; i. e., to be able to dissipate the consequent heat generated within them. The power rating of the resistor, in watts, expresses this capability, assuming the resistor has adequate circulation of air around it.

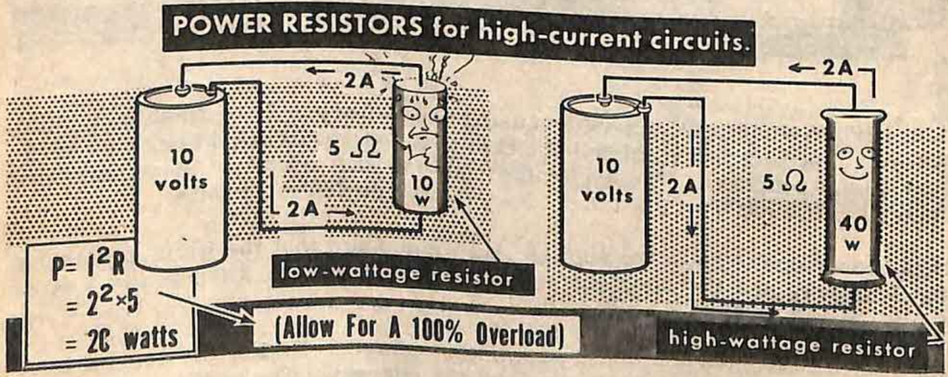
The power rating sets the limit on the maximum amount of current that can flow through the resistor without damaging the resistor element. This is so for all kinds of resistors -- fixed and variable, carbon, deposited metal or any other. In all cases, the power rating applies to the whole resistor and not to a part.

How can we calculate the maximum amount of current which can be permitted to flow in a resistor of a given wattage rating without damaging it? The equation is: $I = \sqrt{\frac{P}{R}}$

Assume a wirewound resistor rated at 20 watts and 5 ohms. What is the maximum amount of current that can be passed through the resistor? Substituting these values in the equation:

$$\text{maximum current} = \sqrt{\frac{20}{5}} = \sqrt{4} = 2 \text{ amperes}$$

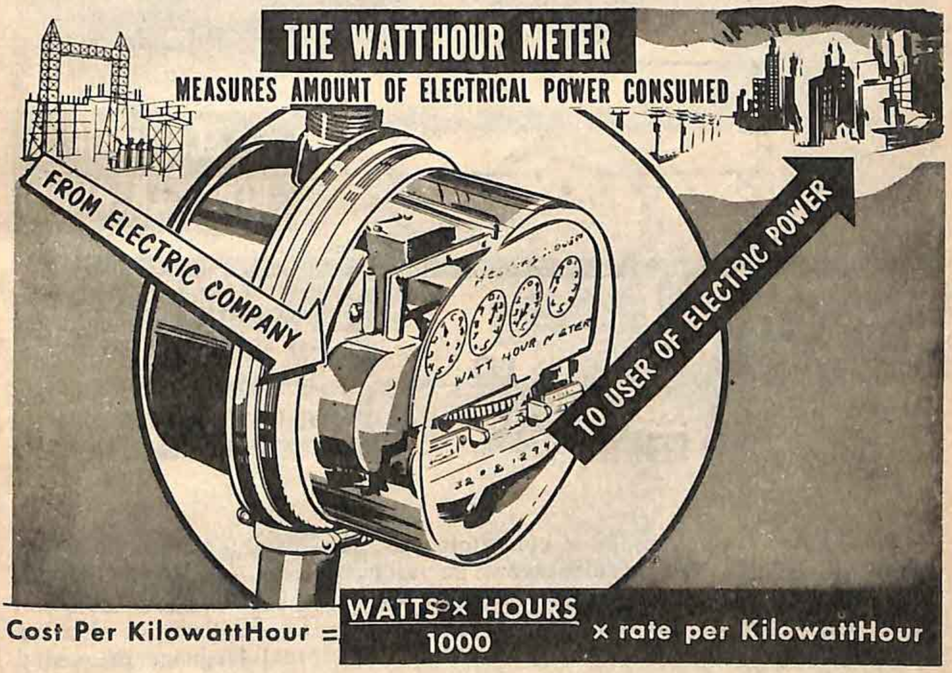
Try to solve the following: The resistor is rated at 0. 5 watt and 5000 ohms. What is the maximum current? Your answer should be . 01 ampere or 10 ma.



It is important to note the power formula $P = I^2R$. As the current through a resistor doubles, the power dissipated by the resistor increases four times. As the current triples, the power dissipation requirement increases nine times. From this, we can see the importance of current flow with regard to power -- it becomes the most important consideration.

The Kilowatthour

We have learned that power represents the rate at which electrical energy is being consumed, or used up. A 50-watt lamp uses electrical power at twice the rate of a 25-watt lamp. Electric utility companies are in the business of selling electricity. Through huge electrical generators turned mostly by water or steam power, the electric companies deliver voltage to homes, offices and industrial plants. No power is consumed, however, until a circuit is closed and current is drawn. Electric companies charge for the use of this power on the basis of how many watts are consumed and for how many hours. From this comes the term watthour. The watthour is obtained by multiplying the number of watts consumed by the number of hours it was consumed. For instance, a 100-watt lamp burning for 10 hours gives us a figure of 1000 watthours. Since the amount of watthours used by a home or industry during the course of a month (a billing period) is usually a very large figure, the kilowatthour (KWH) is used. A kilowatthour equals 1000 watthours.

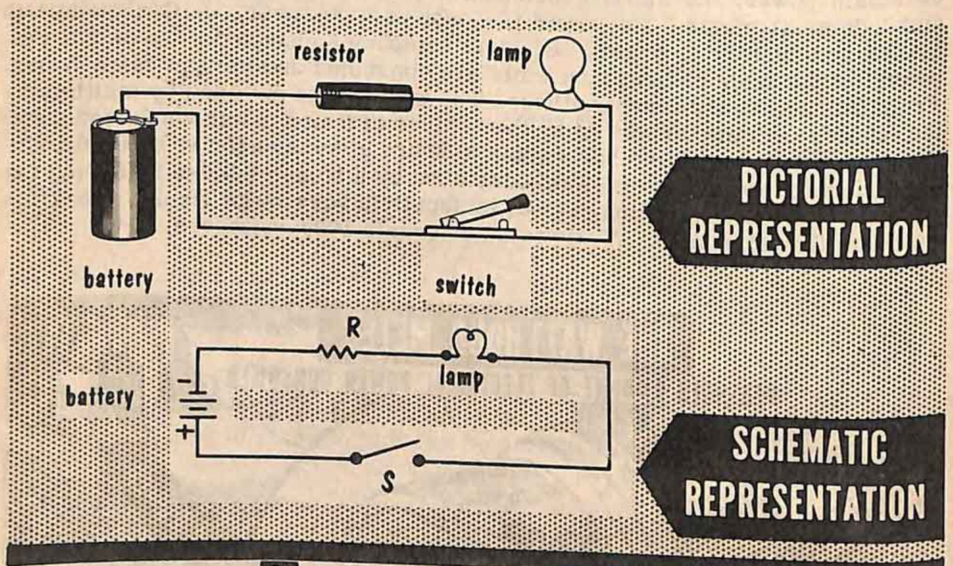

THE WATTHOUR METER
MEASURES AMOUNT OF ELECTRICAL POWER CONSUMED
FROM ELECTRIC COMPANY
TO USER OF ELECTRIC POWER
WATT HOUR METER

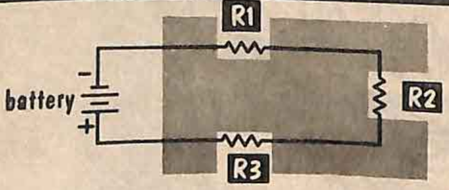
$$\text{Cost Per KilowattHour} = \frac{\text{WATTS} \times \text{HOURS}}{1000} \times \text{rate per KilowattHour}$$

The electric company places a watthour meter at every electrical input. At specified periods, the amount of watthours consumed is read and subtracted from the previous total. A charge is made from this, based on the cost per kilowatthour. For example, an office uses 1000 kilowatthours during a month. At 5 cents per kilowatthour, the cost of electricity would be 5 × 1000, or 5000 cents ($50.00). A special meter is used to measure watts, which we will discuss later.

The Organization of D-C Circuits (Schematic Representation)

We have discussed the meaning of voltage, current, resistance, and power as individual electrical quantities and the units in which these quantities are expressed and compared. To use this information we must apply it to circuits.





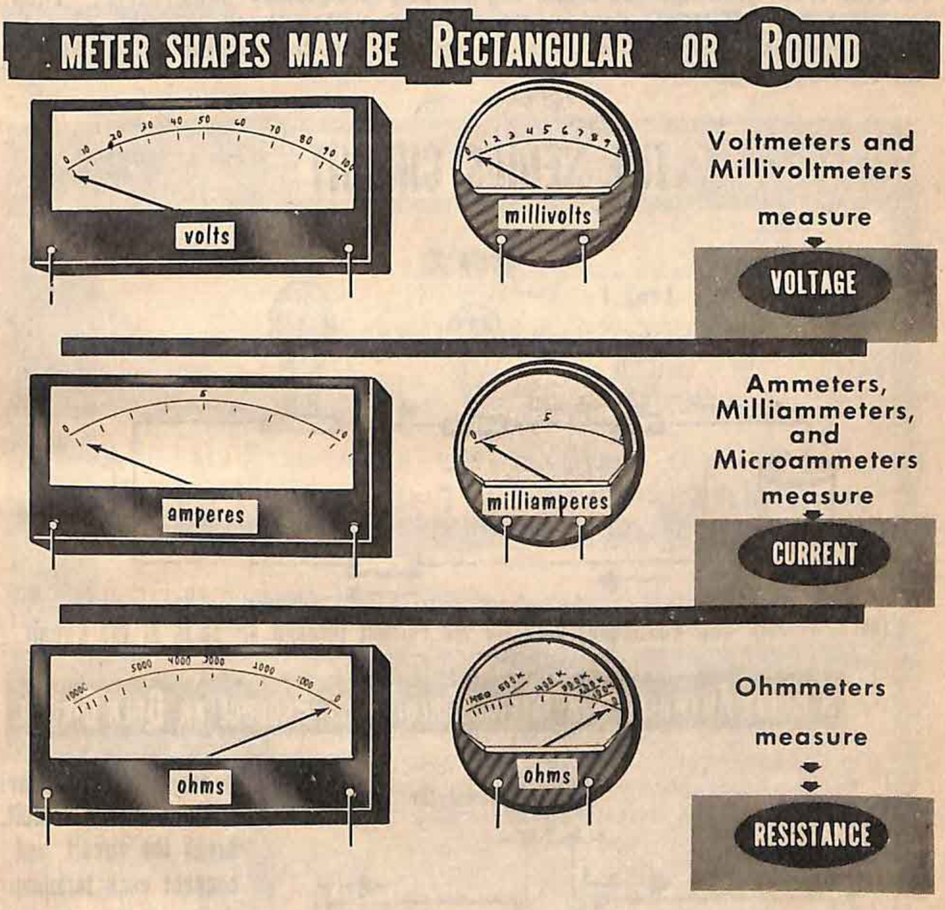
where several of the same type of component are in the same circuit, they are usually numbered.

To understand the principles of electricity, we must be able to recognize and "read" a circuit. The circuits shown so far have been mostly in pictorial form. Another form, known as schematic uses symbols to show the components of a circuit. Schematic representation is the usual way of showing circuitry. In a sense it corresponds to the electrical language presented graphically. We shall start with very few symbols, increasing them as the variety of circuits and electrical components is increased.

Symbolization on the schematic is usually accompanied by two forms of identification: a letter with or without an accompanying numeral, (such as R3, indicating the third resistor in the circuit), and numbers expressing the electrical value of the component (for example, the ohmic value if it is a resistor and possibly the power rating and tolerance). Sometimes a word will appear next to the symbol for purposes of identification (such as LAMP).

Introduction to Measuring Devices

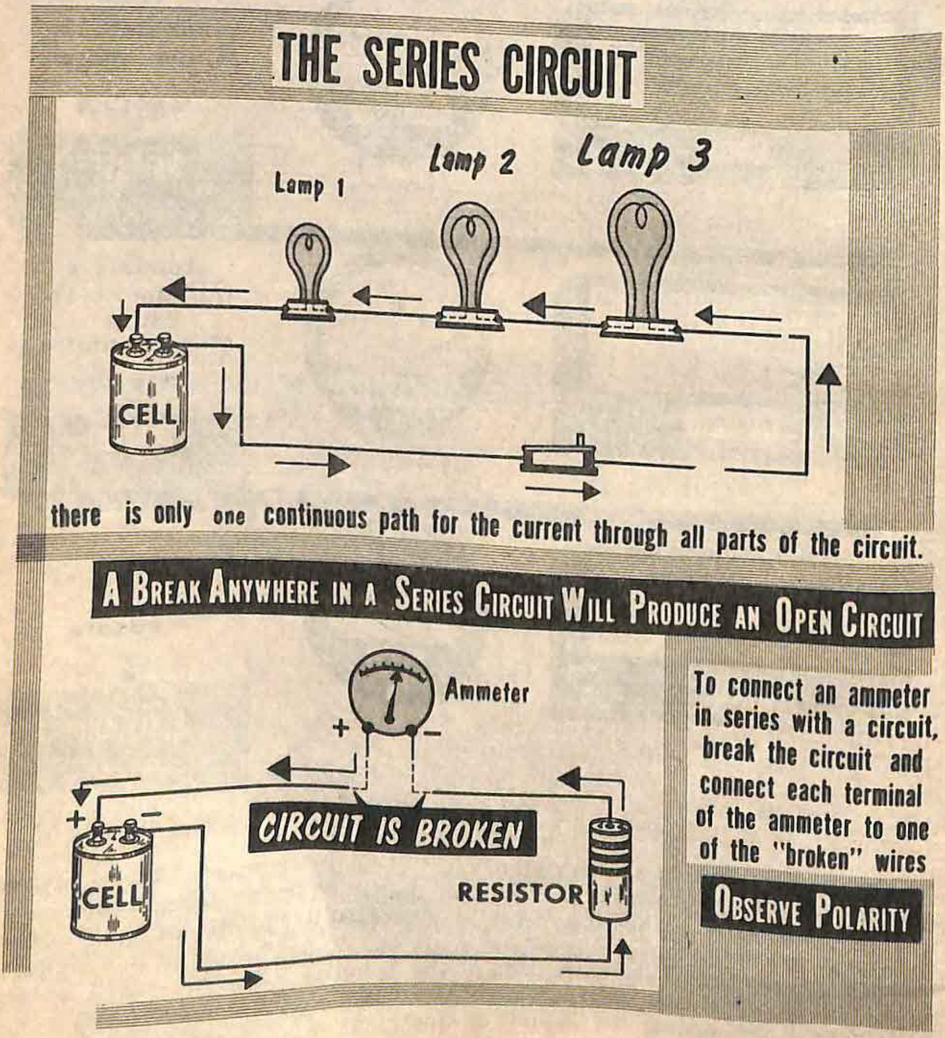
Voltage, current, resistance and electrical power are measurable quantities. Such measurement is done with electrical measuring instruments known as "meters." Although the principles underlying the operation of meters have not yet been discussed, it is nevertheless possible to become familiar with voltmeters that measure voltage, ammeters that measure current, ohmmeters that measure resistance, and wattmeters that measure electrical power.



Meters have calibrated scales on the "face" of the instrument. These scales are marked off (calibrated) in fractions or multiples of the units of the quantity being measured. When the meter is connected to the circuit under measurement, a pointer moves across the scale and comes to rest at the position which corresponds to the magnitude of the quantity being measured at the particular location in the system where the measurement is made. The complete details concerning the theory of electrical meters are given later on.

The Series-Connected or Series Circuit

The terms series-connected or series circuit applies to the arrangement of an electrical circuit in which there is only one continuous path for the flow of the current. A series circuit may contain many individual devices--a battery, numerous resistances, switches, et. al., --but they are so connected that the current must flow through each one. An important characteristic of the series circuit is that a break or opening in any part of this circuit will prevent any current from flowing, and make the circuit completely inoperative. Thus, to insert any additional device into the series circuit, the circuit must be broken, and the new device so connected that all the current in the circuit must flow through it.



THE SERIES CIRCUIT

there is only one continuous path for the current through all parts of the circuit.

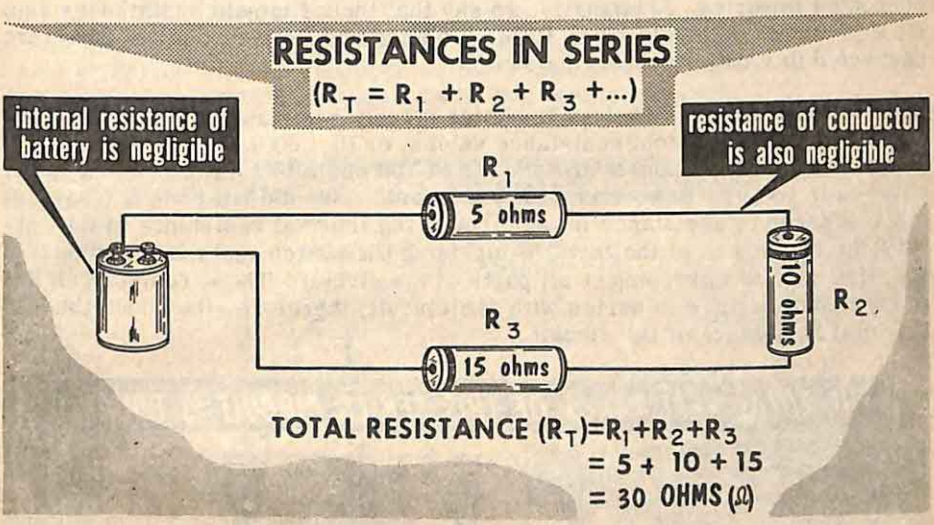
A BREAK ANYWHERE IN A SERIES CIRCUIT WILL PRODUCE AN OPEN CIRCUIT

To connect an ammeter in series with a circuit, break the circuit and connect each terminal of the ammeter to one of the "broken" wires

OBSERVE POLARITY

Determining Resistances in Series (Calculation)

It is not enough to say that resistance exerts control on the amount of current that flows in a circuit. There are many ways in which the control of current by resistance is used.


RESISTANCES IN SERIES
$(R_T = R_1 + R_2 + R_3 + ...)$
internal resistance of battery is negligible
resistance of conductor is also negligible
R_1
5 ohms
10 ohms
R_2
R_3
15 ohms
TOTAL RESISTANCE $(R_T) = R_1 + R_2 + R_3$
$= 5 + 10 + 15$
= 30 OHMS (Ω)

THE TOTAL RESISTANCE OF A SERIES CIRCUIT IS EQUAL TO THE SUM OF THE INDIVIDUAL RESISTANCES

Consider a circuit consisting of a battery (a voltage source), a switch, and a flashlight bulb. The complete circuit is a series circuit because there is only one path for the current. For the moment, all we know about the circuit is that the operating resistance (the "hot" resistance) of the filament is 3 ohms. Everything in the circuit appears normal as judged by the normal brightness of the filament. Now, we raise the bar of the switch to open the circuit; also, we open the circuit at one terminal of the flashlight bulb socket and wire a suitable 3-ohm resistor in series with the circuit. We close the switch and immediately note that the filament glows less brightly. The reason is simply that less current is flowing in the circuit, thereby reducing the circuit current. In other words, resistances in series are additive in their effects. Each resistance contributes opposition to the current. This rule can be stated:

$$R \text{ total or } R_t = R1 + R2 + R3$$

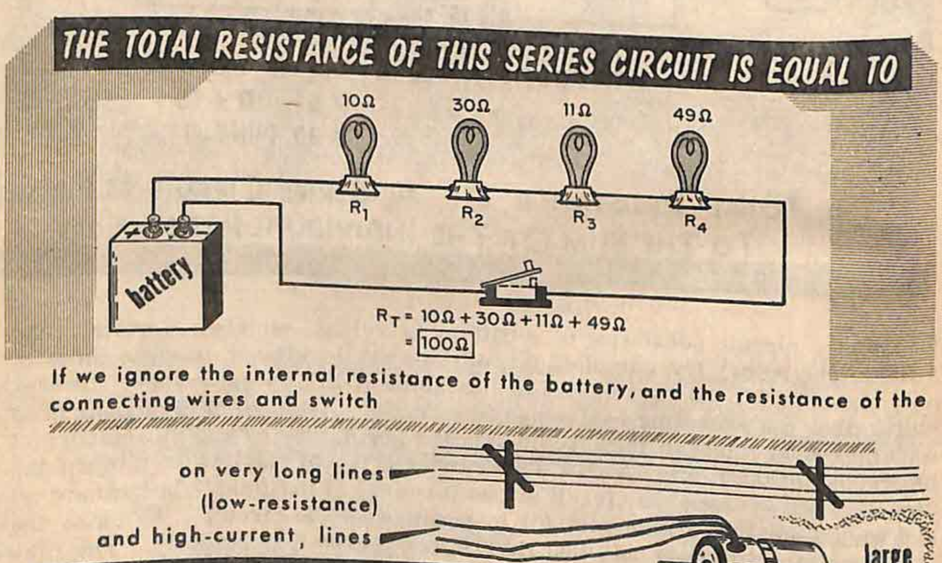
where R1, R2, and R3 are the resistances in series. Applying this formula to the above example, $R_t = 3 + 3 = 6$ ohms total resistance.

Solve this problem. Four resistances are connected in series: R1 = 11 ohms; R2 = 7.3 ohms; R3 = 6.8 ohms; and R4 = 116 ohms. What is the total resistance? Your answer should be 141.1 ohms.

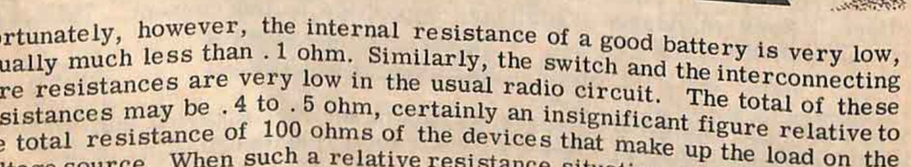
Connecting-Wire Resistance

Now that you know the basic rule for calculating the total resistance of resistances connected in series, we can consider a more advanced case to illustrate an important point. Four different imaginary electric light bulbs are connected in series. Arbitrarily, we say that their filament resistances are: R1 = 10 ohms; R2 = 30 ohms; R3 = 11 ohms; and R4 = 49 ohms. They are connected to a battery through a switch.

Now you are asked, "What is the total circuit resistance?" You get your answer by totaling the four resistance values, or 10 + 30 + 11 + 49 = 100 ohms. For all practical purposes, the answer of 100 ohms is correct. But it is not correct if you are to be technically accurate. We did not consider several other sources of resistance in the circuit: the internal resistance of the battery; the resistance of the metal comprising the switch; and the resistance of the wire used to interconnect all parts of the circuit. These resistances are present and they are in series with the circuit; therefore, they contribute to the total resistance of the circuit.


THE TOTAL RESISTANCE OF THIS SERIES CIRCUIT IS EQUAL TO
10Ω
30Ω
11Ω
49Ω
R_1
R_2
R_3
R_4
battery
$R_T = 10\Omega + 30\Omega + 11\Omega + 49\Omega$
$= \boxed{100\Omega}$

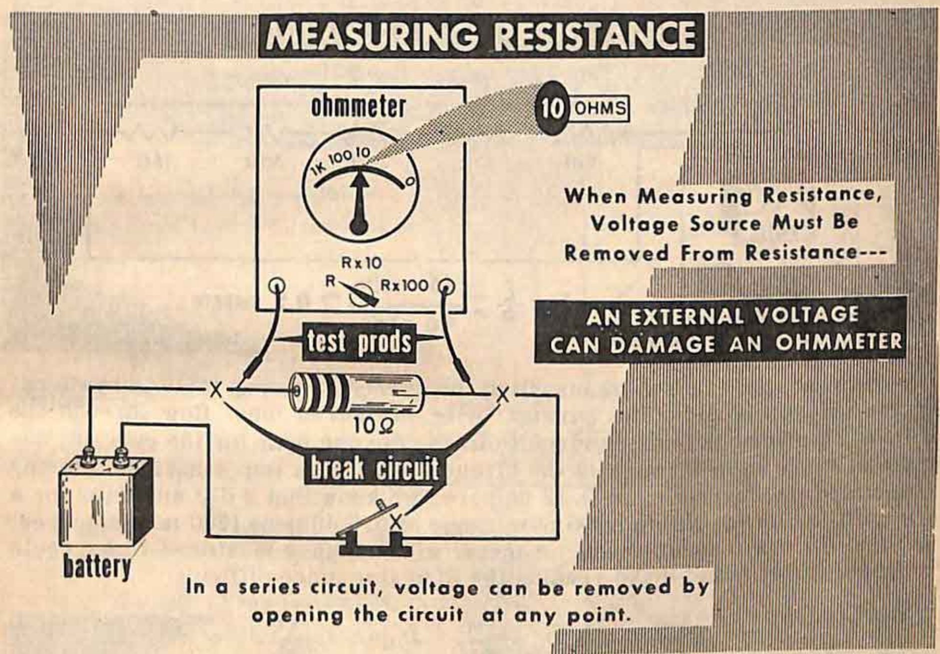
If we ignore the internal resistance of the battery, and the resistance of the connecting wires and switch



Fortunately, however, the internal resistance of a good battery is very low, usually much less than .1 ohm. Similarly, the switch and the interconnecting wire resistances are very low in the usual radio circuit. The total of these resistances may be .4 to .5 ohm, certainly an insignificant figure relative to the total resistance of 100 ohms of the devices that make up the load on the voltage source. When such a relative resistance situation prevails, it is permissible to forget about the battery, switch, and connecting-wire resistances as factors that contribute to the total circuit resistance, and to think only of the resistance made up by the load devices. We shall do this in all future discussions except where noted.

Resistances in Series (Measurement)

The total resistance of resistances in series, or the ohmic value of the individual resistances in a series circuit, can be determined by measurement using an ohmmeter. Because of the electrical characteristics of the ohmmeter, the resistance being measured cannot be part of an electrical circuit in which current is flowing while the measurement is being made. The resistor or device whose resistance is being measured must be disconnected from whatever source of voltage may be acting on the circuit.



When Measuring Resistance, Voltage Source Must Be Removed From Resistance---

AN EXTERNAL VOLTAGE CAN DAMAGE AN OHMMETER

In a series circuit, voltage can be removed by opening the circuit at any point.

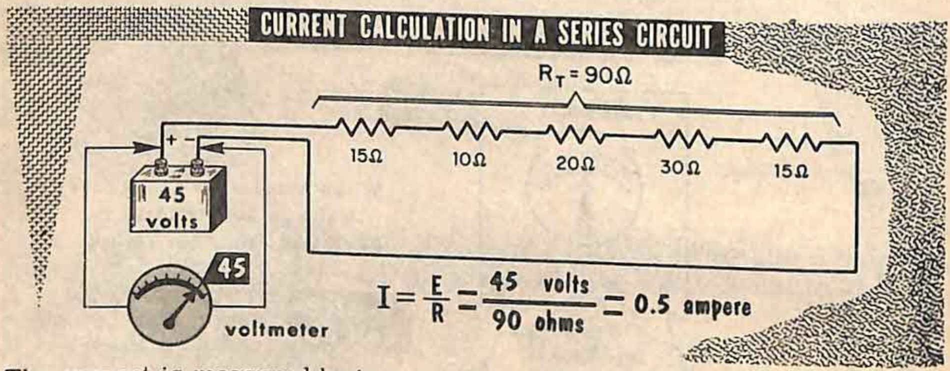
The measurement is made by connecting one test prod of the ohmmeter to one of the terminals of the device or resistor (alone or a series chain), and the other test prod to the other terminal of the resistance, and reading the indication on the scale. Although more will be said later, all ohmmeters afford different ranges of resistance measurement by manipulating a selector switch. The ideal condition for accurate measurement is when the indication of the resistance is at the middle to low end of the scale.

A very important fact to bear in mind when measuring the resistance of lamp filaments is that there is a major change in the resistance when the filament is cold and when it is hot. Hot means that the filament is drawing current. The resistance of a hot filament is higher. More important, the ohmmeter cannot be used to measure the resistance of a glowing lamp filament. Damage to the instrument is sure to result. Every device whose function is to convert electric energy to heat energy has a "cold" and a "hot" resistance.

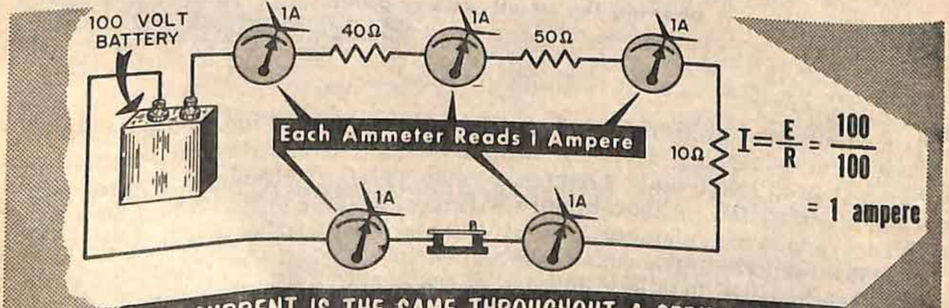
Current in a Series Circuit (Calculation and Measurement)

There are two ways of determining the amount of current in a series circuit. One is by calculation, using Ohm's Law for current ($I = E/R$). Two quantities must be known -- the total resistance (R) of the series circuit and the applied voltage (E). The second method is by measurement, using an appropriate current meter. As a typical case, consider four resistors -- R1 = 10 ohms, R2 = 30 ohms, R3 = 11 ohms and R4 = 49 ohms -- joined in series and connected across a 12-volt source. The total circuit resistance is 100 ohms. How much current is flowing in the circuit?

CURRENT CALCULATION IN A SERIES CIRCUIT


$R_T = 90\Omega$
+
-
15Ω
10Ω
20Ω
30Ω
15Ω
45 volts
45
voltmeter
$I = \frac{E}{R} = \frac{45 \text{ volts}}{90 \text{ ohms}} = 0.5$ ampere

The current is measured by inserting the current-reading meter anywhere in the series circuit. The current being measured must flow through the meter. Because the series circuit offers only one path for the current, the current is the same throughout the circuit. This is an important rule. Having calculated the current to be 0.12 ampere, we know that a d-c ammeter (or a d-c milliammeter) with a maximum range of 0.5 ampere (500 milliamperes) is ideal for the measurement. A meter with a higher maximum range could be used, but it would make reading the indicator more difficult.

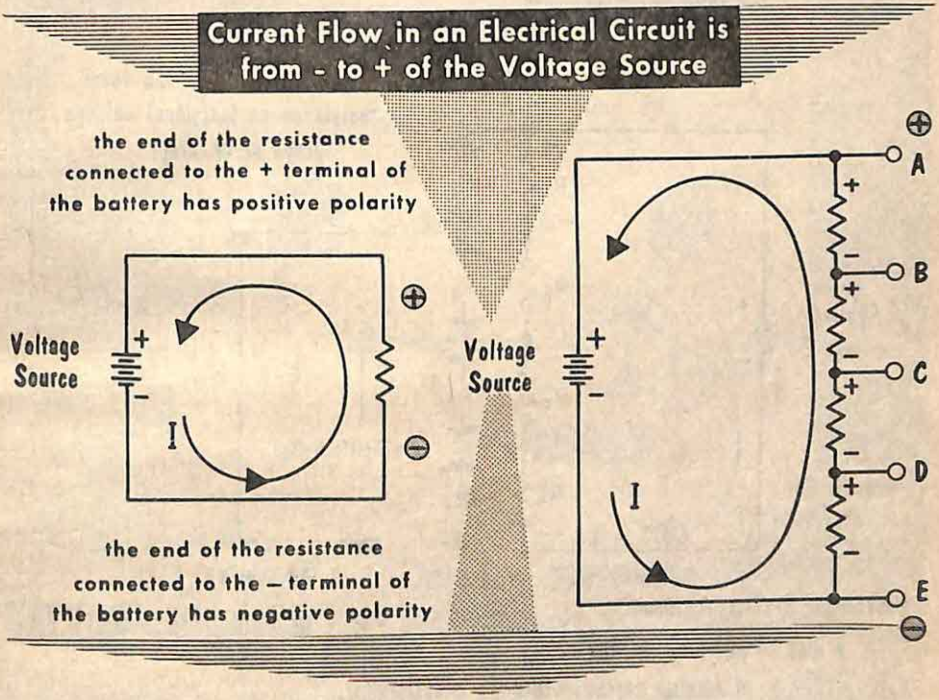

100 VOLT BATTERY
1A
40Ω
1A
50Ω
1A
Each Ammeter Reads 1 Ampere
10Ω
$I = \frac{E}{R} = \frac{100}{100}$
= 1 ampere
1A
1A

THE CURRENT IS THE SAME THROUGHOUT A SERIES CIRCUIT

Try this exercise problem. Four filaments totaling 90-ohms resistance are connected in series. How much resistance must be added in series with the filament string to limit the current to 0.12 ampere when the battery voltage is 12 volts? ($R = \frac{E}{I} = \frac{12}{.12} = 100$ ohms, total R. Since we already have 90 ohms, we must add 10 ohms.) Is your answer 10 ohms?

Polarity in Series Circuits

Voltage polarity in series circuits determines the proper usage of a d-c measuring device. A series circuit consisting of a single resistor connected across a voltage source presents a simple set of polarity conditions. That end of the resistor connected to the positive terminal of the voltage source is the positive end of the resistor; that end of the resistor connected to the negative terminal of the voltage source is the negative end of the resistor. If we use the direction of current flow as indicated, the same polarities prevail -- the end at which the current presumably enters the resistance load is the negative end; where it leaves the resistance load is the positive end.



Current Flow in an Electrical Circuit is from - to + of the Voltage Source

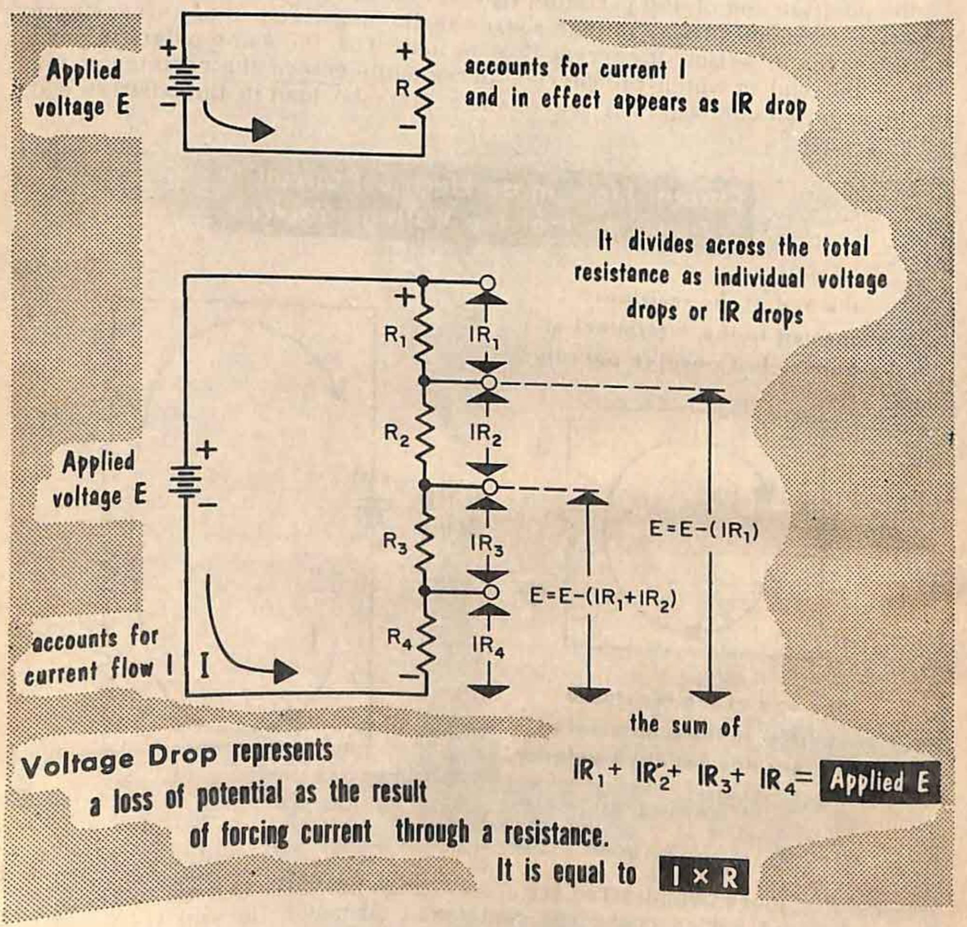
the end of the resistance connected to the + terminal of the battery has positive polarity

the end of the resistance connected to the – terminal of the battery has negative polarity

A somewhat more complicated set of conditions prevails in a circuit containing a string of series-connected resistors. Although the end terminals of the series string have positive and negative polarity just as in the single-resistance circuit, points along the series string (other than the two extremes) have dual polarity. Point (A), for example, has a positive polarity relative to any point along the series chain. Point (B), on the other hand, is negative relative to point (A) but positive relative to points (C), (D) and (E). Relative to point (B), the current enters at (C), but leaves at (B). On the other hand, relative to point (A), the current enters at (B), thereby making this point negative while it leaves at (A), making this point positive. If we take point (E) as the most negative reference point, points (D), (C), (B) and (A) are positive with respect to point (E).

Voltage Drop in Series Circuits

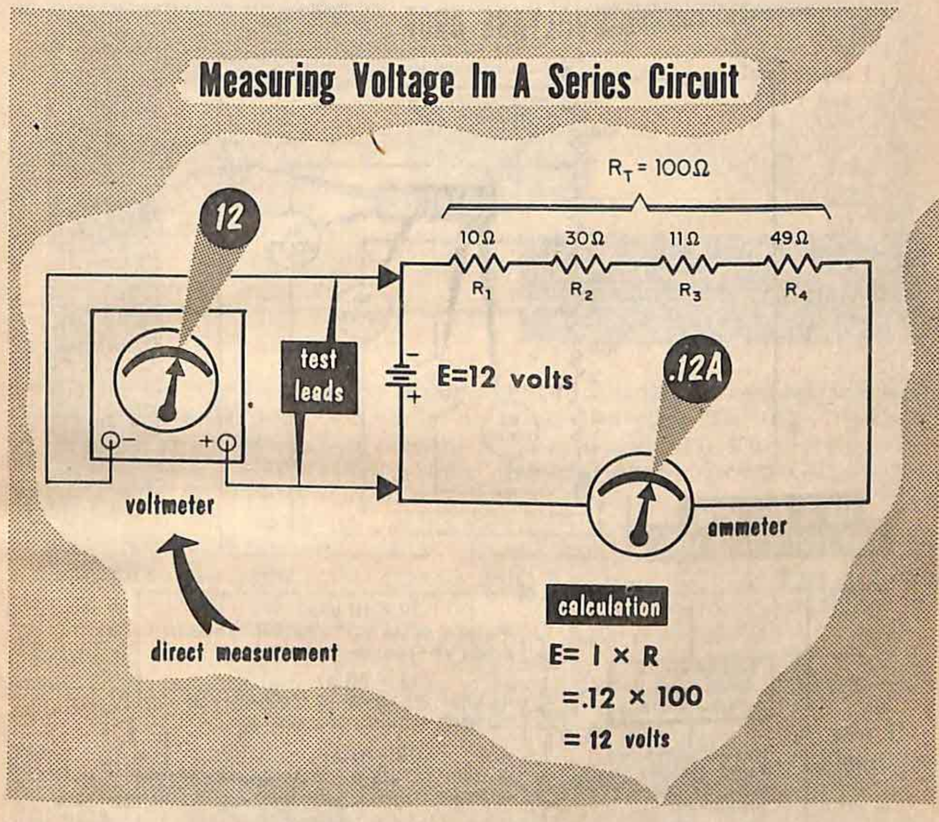
Voltage drop , or IR drop as it is also known, is interpreted in two ways. In one sense, it means the voltage that appears across any resistor R through which a current I is flowing. The same thought is conveyed when the product of IR is referred to as simply voltage without adding the word drop .


Applied voltage E
+
−
+
R
−
accounts for current I and in effect appears as IR drop
It divides across the total resistance as individual voltage drops or IR drops
+
R_1
IR_1
R_2
IR_2
Applied voltage E
+
−
R_3
IR_3
$E = E - (IR_1)$
$E = E - (IR_1 + IR_2)$
accounts for current flow I
I
R_4
IR_4
−
the sum of
$IR_1 + IR_2 + IR_3 + IR_4 =$ Applied E
Voltage Drop represents a loss of potential as the result of forcing current through a resistance.
It is equal to I × R

The second meaning of voltage drop (or IR drop) relates expressly to series circuits; meaning that it refers to the voltage which appears across each resistance R in a series chain when a current I is flowing through the chain. Since the sum of the individual resistances in a series circuit is the total resistance of the circuit (hence, determines the circuit current I for a given applied voltage), the sum of the individual voltage drops equals the applied voltage. Utility-wise, voltage drop is the means whereby a d-c voltage that is less than the applied voltage can be made available at a particular point in a series circuit. This function of the series circuit is the reason for its being called a voltage divider.

Determining Applied Voltage in a Series D-C Circuit

The applied voltage in a series d-c circuit can be calculated when circuit current and total resistance are known, or it can be measured directly with a d-c voltmeter. When I and total R are known, Ohm's Law for voltage, $E = IR$, is used. It is applicable to all d-c circuits.



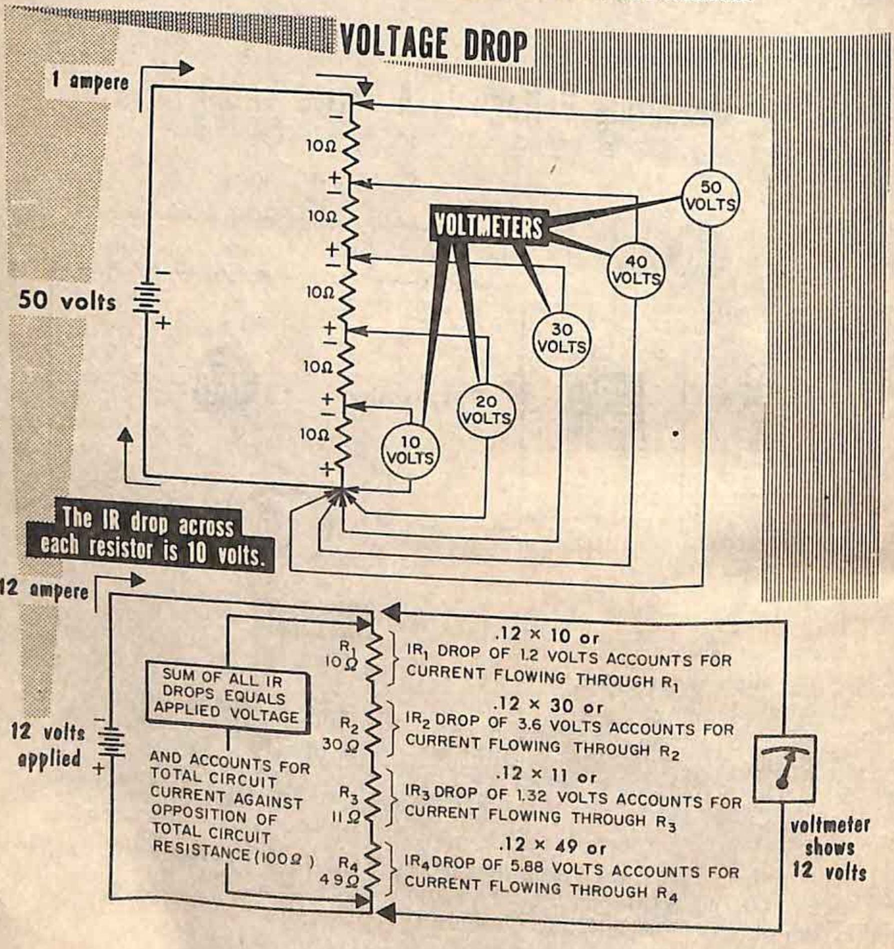
In the circuit used for the example, the current is 0.12 ampere (120 milliamperes) and the total circuit resistance made up of R1, R2, R3 and R4 equals 100 ohms. The applied voltage is:

$$E = I \times R, \text{ or } E = .12 \times 100 = 12 \text{ volts.}$$

The 12 volts applied causes 0.12 ampere to flow through the series circuit. We can reaffirm this by connecting a suitable d-c voltmeter across the circuit at the terminals of the voltage source. The positive test lead from the voltmeter is connected to the positive-polarity side of the circuit, and the negative test lead (sometimes marked common) is connected to the negative-polarity side of the circuit. A suitable voltmeter would be one with a full-scale range of from 30 to perhaps 50 volts, so that the 12 volts indication would be easily readable.

Calculating and Measuring Voltage Drop in Series Circuits

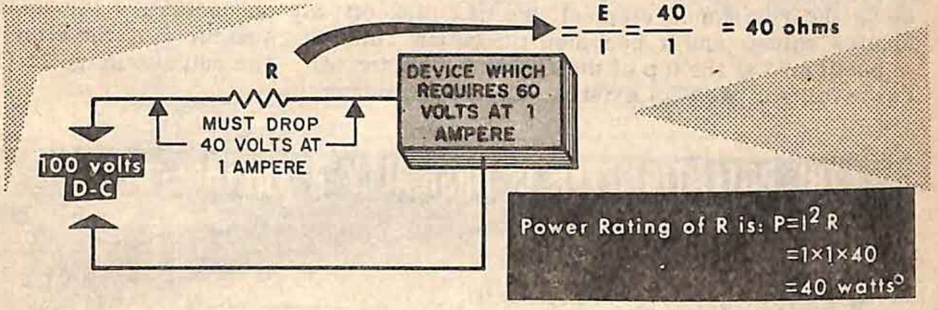
Voltage drop or IR drop can be calculated, or measured with a suitable voltmeter. To calculate voltage drop, the current and the resistance must be known. Ohm's Law for voltage (E = I × R) is then used, I being the circuit current and R representing the ohmic value of each resistance.


VOLTAGE DROP
1 ampere
10Ω
10Ω
10Ω
10Ω
10Ω
50 volts
VOLTMETERS
50 VOLTS
40 VOLTS
30 VOLTS
20 VOLTS
10 VOLTS
The IR drop across each resistor is 10 volts.
.12 ampere
R_1 10Ω
R_2 30Ω
R_3 11Ω
R_4 49Ω
SUM OF ALL IR DROPS EQUALS APPLIED VOLTAGE
AND ACCOUNTS FOR TOTAL CIRCUIT CURRENT AGAINST OPPOSITION OF TOTAL CIRCUIT RESISTANCE (100Ω)
12 volts applied
.12 × 10 or IR_1 DROP OF 1.2 VOLTS ACCOUNTS FOR CURRENT FLOWING THROUGH R_1
.12 × 30 or IR_2 DROP OF 3.6 VOLTS ACCOUNTS FOR CURRENT FLOWING THROUGH R_2
.12 × 11 or IR_3 DROP OF 1.32 VOLTS ACCOUNTS FOR CURRENT FLOWING THROUGH R_3
.12 × 49 or IR_4 DROP OF 5.88 VOLTS ACCOUNTS FOR CURRENT FLOWING THROUGH R_4
voltmeter shows 12 volts

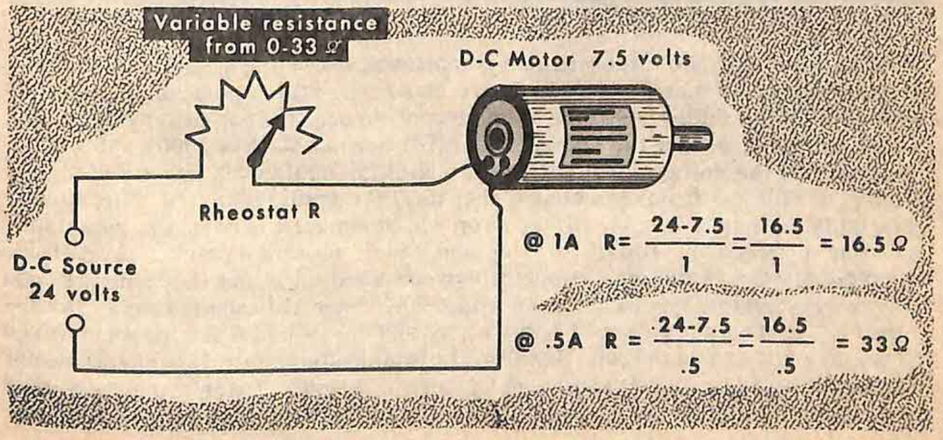
To measure voltage drop, a suitable voltmeter is connected across the resistance (or resistances) through which the current is flowing. Across means that the two leads from the voltmeter are connected to the limits of the circuit or that part of the circuit where the voltage is to be measured. In the examples shown, the voltage drop across the entire series train, as well as across its individual elements, is being measured. The voltage developed across two or more adjacent resistors also is measurable. Note that the polarity of the voltage differs at different points along the series-connected resistances, several points having dual polarity.

Applying Voltage Drop

How is voltage drop used? Imagine the following situation: a d-c device that requires 60 volts and 1 ampere for its operation must be used with a d-c voltage source which delivers 100 volts. How can this be done? The answer is to connect the device in series with a voltage-dropping resistor which would reduce the voltage amount to the difference between the available voltage (100) and the required voltage (60).

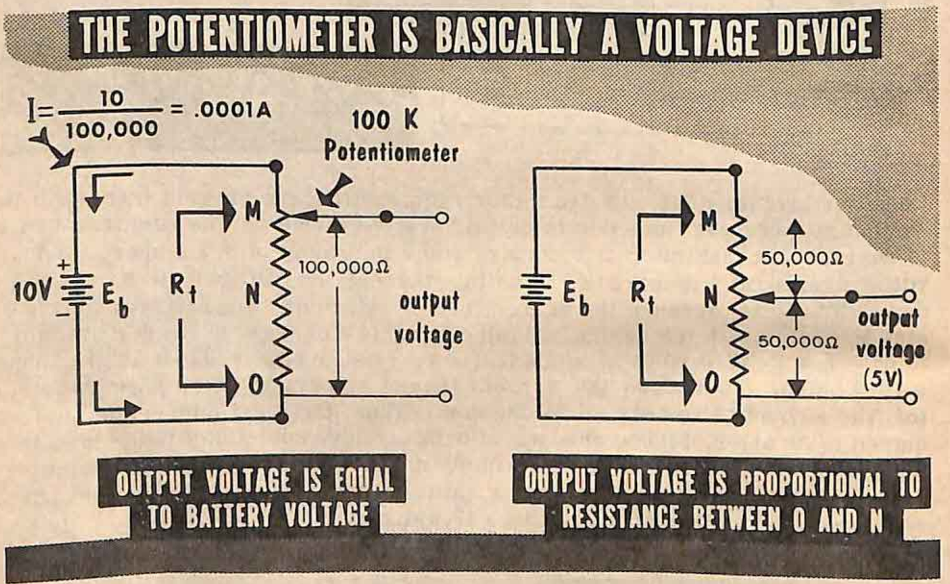

$= \frac{E}{I} = \frac{40}{1}$ = 40 ohms
R
DEVICE WHICH REQUIRES 60 VOLTS AT 1 AMPERE
MUST DROP 40 VOLTS AT 1 AMPERE
100 volts D-C
Power Rating of R is: $P = I^2R$
$= 1 \times 1 \times 40$
$= 40$ watts

Consider another case. A d-c motor requires that the current through it be varied at irregular intervals to suit a variety of needs. The required range of current is a maximum of 1 ampere and a minimum of 0.5 ampere. The voltage rating at 1 ampere is 7.5 volts, whereas the voltage source is 24 volts d-c. How do we arrange the current needs? By connecting a wirewound rheostat in series with the device. At full current (1 ampere), a voltage drop equal to 24 - 7.5 = 16.5 volts is needed. The resistance required is R = E/I = 16.5/1 = 16.5 ohms. To reduce the current from 1 ampere to .5 ampere requires that the amount of resistance be doubled. Thus, the maximum resistance required is 33 ohms. Since a rheostat affords variable resistance from zero to a maximum, a rheostat rated at 33 ohms maximum and capable of passing 1 ampere will be adequate. The power rating is determined by the highest current flow or $P = I^2R = (1 \times 1) \times 33 = 33$ watts.


Variable resistance from 0-33 Ω
D-C Motor 7.5 volts
Rheostat R
D-C Source 24 volts
@ 1A $R = \frac{24-7.5}{1} = \frac{16.5}{1} = 16.5\,\Omega$
@ .5A $R = \frac{24-7.5}{.5} = \frac{16.5}{.5} = 33\,\Omega$

Applying Voltage Drop (Cont'd) (Potentiometer Voltage Divider)

A frequently used arrangement found in radio systems makes use of a potentiometer as a voltage divider. It is a means of obtaining a variable voltage from a constant voltage source. Assume a voltage source E_b (although it need not always be a battery) and a potentiometer with a total resistance R_t of 100,000 ohms. The circuit current is $I = E/R_t = 10/100,000 = .0001$ ampere, or 100 microamperes. The entire 10 volts applied appears across the potentiometer element as a fixed voltage drop. By moving the slider along the resistance element, we can pick off any percentage of the total applied voltage and it becomes the output voltage. Assume that the slider is positioned at the top of the element (position M). The output voltage M-O is the full voltage (E_b) existing across the element.



THE POTENTIOMETER IS BASICALLY A VOLTAGE DEVICE

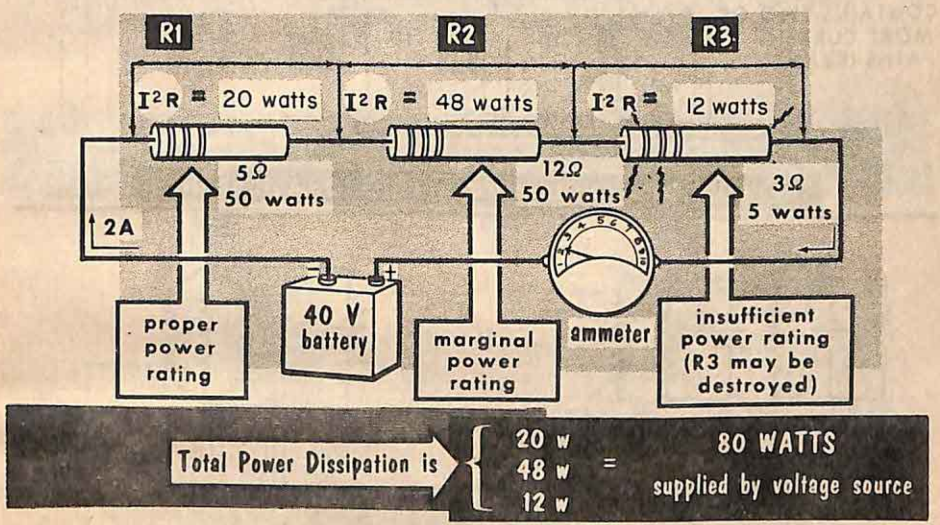
OUTPUT VOLTAGE IS EQUAL TO BATTERY VOLTAGE

OUTPUT VOLTAGE IS PROPORTIONAL TO RESISTANCE BETWEEN 0 AND N

Now assume that the slider is moved half-way down the resistance element to position N, so that 50,000 ohms are above the slider position and 50,000 ohms below the slider position. The current through the potentiometer is still .0001 ampere, so that the voltage drop (IR) across M-N is $.0001 \times 50,000 = 5$ volts, and the voltage drop (IR) across N-O is $.0001 \times 50,000 = 5$ volts. If these two voltage drops are added, they total the applied voltage. The voltage available as output is the voltage drop which appears across the resistance element between the slider location and the 0 reference point. The voltage drop across the resistance element between location M and the slider is, you might say, wasted. By moving the slider anywhere between 0 and M, any desired value of output voltage between zero and the value of the applied voltage is made available as output. Usually, the total resistance of the potentiometer chosen is high, so that the current through it is low. Potentiometer voltage dividers are usually used when the current drawn through the slider is very low.

Power in the Series Circuit

As current flows through a series circuit, it flows through each resistance in that circuit. As we have seen, there is a voltage drop, or IR drop, as the result of current flowing through that resistance. In the process of forcing electrons through a resistance, a certain amount of power is "wasted," or consumed. This power is equal to I^2R, and is often referred to as the $\underline{I^2R \text{ loss}}$. Since power is measured in terms of watts, virtually all electrical equipment is rated in terms of how many watts it consumes or dissipates. Resistors of 1 watt or more usually have their power ratings printed right on the body of the resistor.

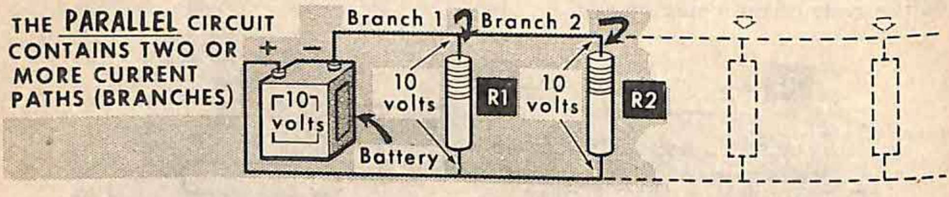


In the illustration, we have a simple series circuit using three resistors in series. With two amperes flowing through the circuit ($I = 40/20$), the power dissipated in R1 is 20 watts, R2 48 watts, and R3 12 watts. A resistor must be of sufficient size and proper design to dissipate the heat produced within itself, and to be safe, circuit designers usually use a resistor having a wattage rating of twice that which is necessary. R1, a 50-watt resistor, will easily handle the 20 watts dissipated in it, and may feel almost cool to the touch. R2 is a 50-watt resistor that must handle 48 watts dissipation. This resistor can run warm to very hot, depending upon the circulation of air around it. R3, a 5-watt resistor having 12 watts dissipated in it, will become extremely hot and will most likely be destroyed if this condition is maintained for any length of time.

The total power consumed by the three resistors is 80 watts, and this power must be supplied by the battery or other source of power. High wattage resistors, of 2 watts or more, should generally be located away from other components that may be damaged from the heat. In a series circuit, the total power supplied by the voltage source is equal to the sum of all the I^2R losses in the circuit.

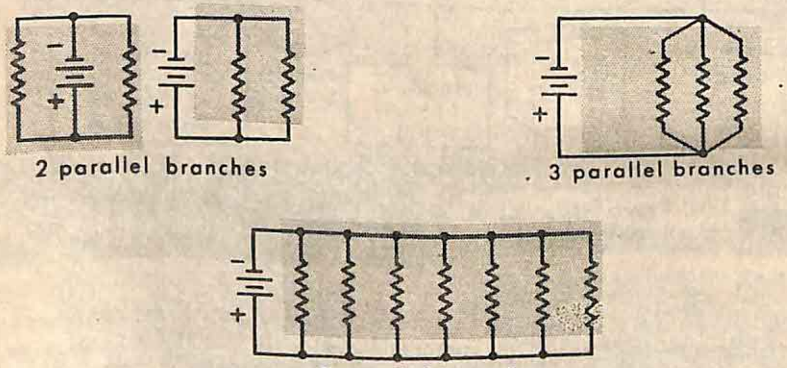
Parallel Circuits

The parallel-connected or parallel circuit is a second type of circuit arrangement. The term shunt-connected or shunt circuit is also used to describe this circuit arrangement. In the parallel circuit, the total battery or source voltage is applied across each and every electrical device in the circuit. The connection is such that each electrical device connected to the source acts independently of each other. The circuit that each device is connected into is called a branch, and the full source voltage is applied to each of these.



THE **PARALLEL** CIRCUIT CONTAINS TWO OR MORE CURRENT PATHS (BRANCHES)

THE FULL BATTERY VOLTAGE IS APPLIED TO EACH BRANCH



2 parallel branches

3 parallel branches

7 parallel branches

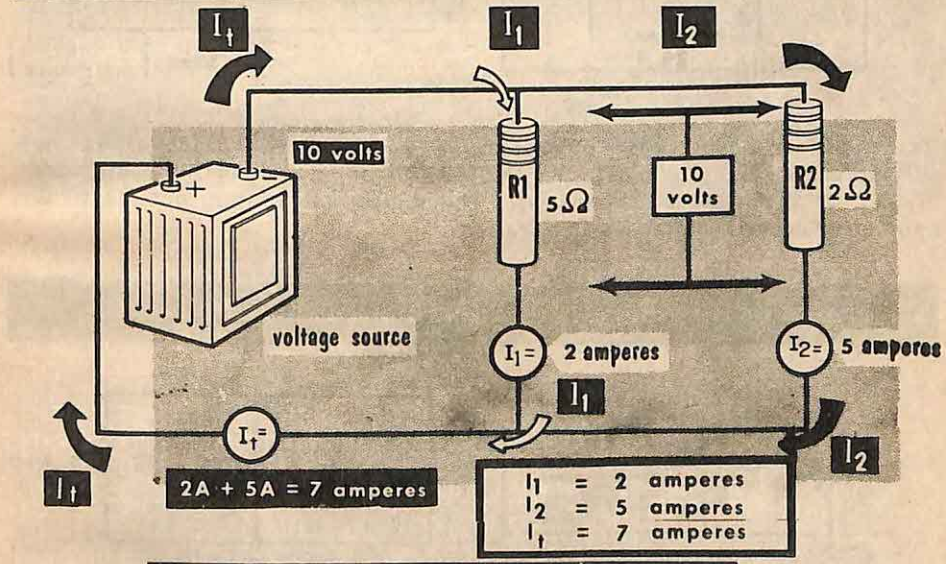
schematic diagrams of parallel circuits

The parallel circuit is used in all homes, offices, and industry. When you turn on a lamp or other electrical device in the home, the full line voltage is applied to that device. In addition, when a lamp is turned off, it has no effect on other lamps or electrical devices. There is no limit to how many branches a parallel circuit might contain. Of course, if there are too many branches, or if the current drain from some branches becomes too great, the voltage source may be unable to supply the necessary power, and the result will be a lowering of the line voltage. Schematically, we show the branches of a parallel circuit tied together to a common point, or tied to two parallel lines drawn from the positive and negative terminals of the voltage-source symbol.

Current in a Parallel Circuit

We have seen that in the parallel circuit, two or more electrical devices are connected across a voltage source and act independently of each other. Since the total voltage is applied to each branch, the current flow in each branch would be determined by the resistance of each branch. If the voltage source is 10 volts and the resistance of one branch is 5 ohms, the current through that branch would be 2 amperes. If the second branch had a resistance of 2 ohms, the current through it would be 5 amperes. Although each branch operates completely independent of the other branches, there is one point they have in common -- their individual branch currents combine at the terminals of the voltage source to form a total current (I_t) for that circuit. In our example, the total current would be 7 amperes, or the sum of all the individual branch currents.

IN A PARALLEL CIRCUIT THE TOTAL CURRENT IS EQUAL TO THE SUM OF ALL THE INDIVIDUAL BRANCH CURRENTS

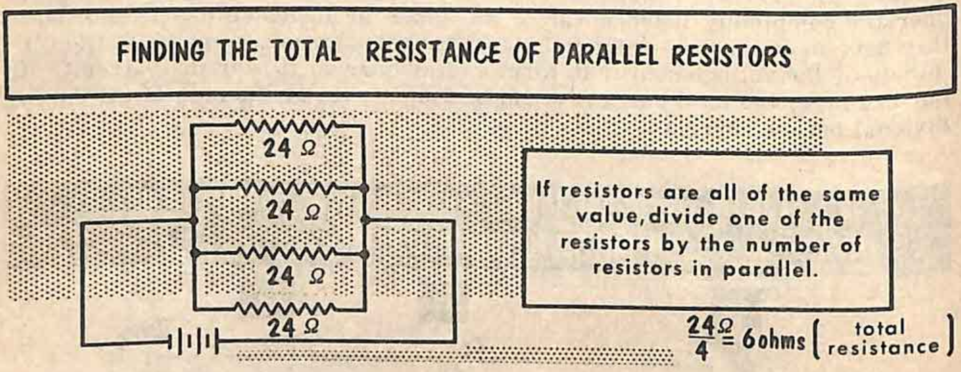


Adding more branches Increases Total Current

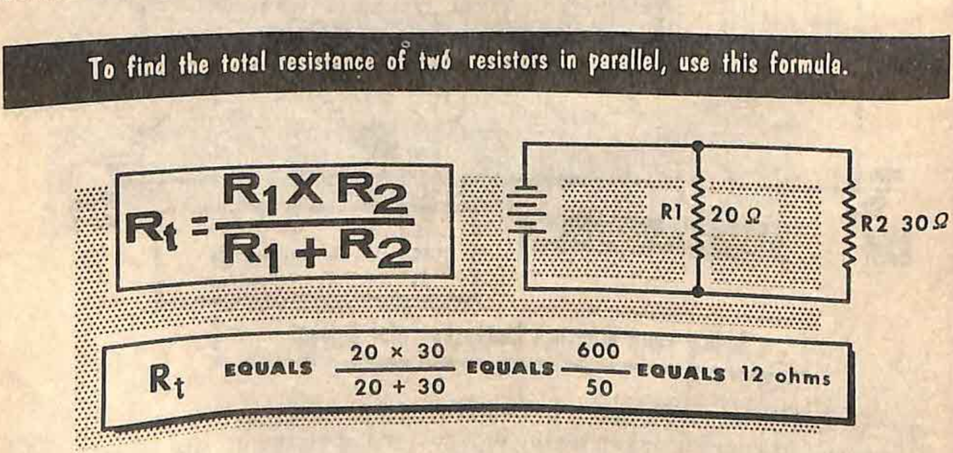
The amount of branches that can be used in a parallel circuit depends upon the amount of current drawn by the devices and upon the ability of the wires to conduct the current without overheating. Circuits containing high-current devices such as motors and heating units have very few branches; those containing low-current devices such as lamps, small radios, etc., may have many branches. The wiring in most homes permits a total circuit current of from 15 to 20 amperes, and contains a fuse which will "blow out" and break the circuit should the sum of the branch currents exceed the rating of the fuse.

Computing Resistances in Parallel

Current in parallel circuits can be measured or computed. Familiarity with the latter process is essential to be able to analyze a parallel circuit. To compute current, circuit resistance must be known. For the purposes of this explanation, we shall neglect the connecting-wire and battery resistances. Several rules related to parallel resistances help to make the calculation easier. They should be remembered.


FINDING THE TOTAL RESISTANCE OF PARALLEL RESISTORS
24 Ω
24 Ω
24 Ω
24 Ω
If resistors are all of the same value, divide one of the resistors by the number of resistors in parallel.
24Ω/4 = 6 ohms (total resistance)

Rule 1. When equal values of resistance are connected in parallel, the resultant resistance is equal to the ohmic value of any one of the resistances divided by the number in parallel. The method of solution applies to any number of equal resistances in parallel.


To find the total resistance of two resistors in parallel, use this formula.
Rt = (R1 X R2)/(R1 + R2)
R1 20 Ω
R2 30 Ω
Rt EQUALS (20 × 30)/(20 + 30) EQUALS 600/50 EQUALS 12 ohms

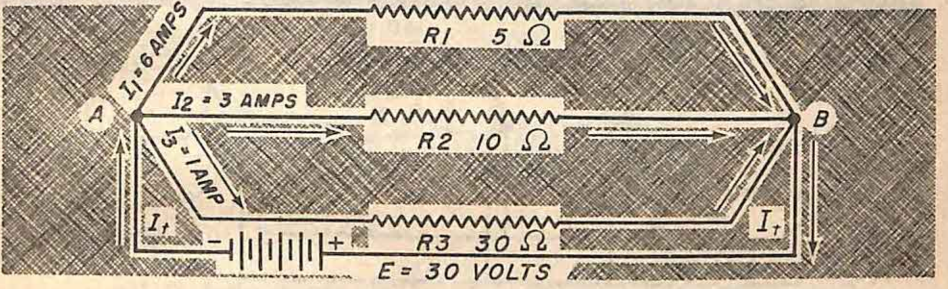
Rule 2. Another rule involves the use of multiplication, addition and division, and applies to any two unequal values of resistance in parallel. It states that the result of two unequal resistances in parallel is equal to the product of their ohmic values divided by the sum of their ohmic value. Rule 1 is, of course, much more convenient to use when the resistances happen to be of equal ohmic value.

Calculating Current in a Parallel Circuit

In a parallel circuit, the same voltage is applied across each of the parallel resistors. In the illustration, the voltage applied across R1, R2, and R3 is 30 volts, the same as the source voltage, E. Current flows from the negative terminal of the source to point A, where it divides and passes through R1, R2, and R3 to point B and back to the positive terminal of the source voltage. The amount of current flowing through each branch depends on the source voltage and on the resistance of that branch. The lower the resistance of the branch, the higher the current will be through that branch. The individual currents can be found by applying Ohm's law to the individual resistors. Thus,

$I1 = \frac{E}{R1} = \frac{30}{5} = 6$ amperes; $I2 = \frac{E}{R2} = \frac{30}{10} = 3$ amperes; $I3 = \frac{E}{R3} = \frac{30}{30} = 1$ ampere.

The total current, I_t, is equal to the sum of the currents through the individual branches, which is 10 amperes.



To find the total resistance R_t in the circuit, Ohm's law is first used to find each of the branch currents. Using the formula above, $\frac{E}{R_t} = \frac{E}{R1} + \frac{E}{R2} + \frac{E}{R3}$; and,

$$\frac{E}{R_t} = E\left(\frac{1}{R1} + \frac{1}{R2} + \frac{1}{R3}\right)$$

Both sides of this equation may be divided by E without changing the value of the equation, therefore: $\frac{1}{R_t} = \frac{1}{R1} + \frac{1}{R2} + \frac{1}{R3}$

The fraction $\frac{1}{R_t}$ is the reciprocal of the total resistance of the parallel circuit.

The reciprocal of a number is the number divided into 1, (e. g., the reciprocal of 5 is $\frac{1}{5}$.) The reciprocal of the total resistance of a parallel circuit is equal to the sum of the reciprocals of all the branches.

Using the above to find the total resistance of the parallel circuit, $\frac{1}{R_t} = \frac{1}{5} + \frac{1}{10} + \frac{1}{30}$; and with the least common denominator of 30, you have,

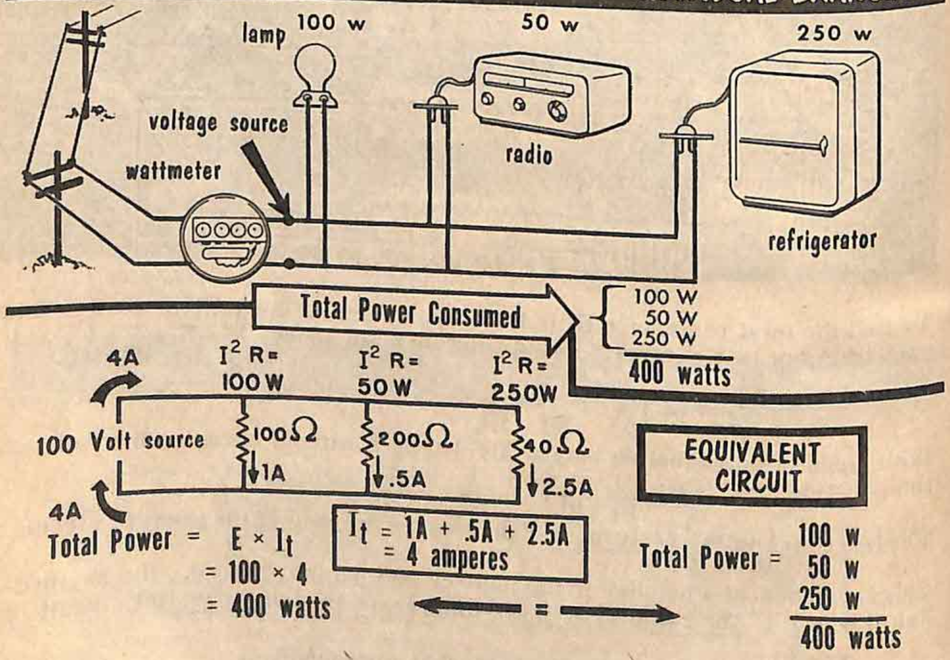
$$\frac{1}{R_t} = \frac{6}{30} + \frac{3}{30} + \frac{1}{30} = \frac{10}{30}$$

Taking the reciprocals of both sides (dividing them into 1), $R_t = \frac{30}{10} = 3$ ohms.

Power in Parallel D-C Circuits

As we studied in series circuits, a power loss takes place in a resistance as the result of current flowing through it. This power loss is equal to I2R, and refers to each and every resistor in the parallel circuit. Each branch of a parallel circuit contains a resistance, and each of the resistances has the same voltage (the source voltage) applied across it. Thus, the current through each branch would be determined by the formula I = E/R. Knowing the current in each branch, we can now compute the power consumed by each branch. We have also seen that each branch circuit operates independently of the others. Thus, the total power consumed by a parallel circuit is equal to the power consumed by all the individual branches.

TOTAL POWER CONSUMED BY A PARALLEL CIRCUIT IS EQUAL TO THE SUM OF THE POWER CONSUMED BY THE INDIVIDUAL BRANCHES

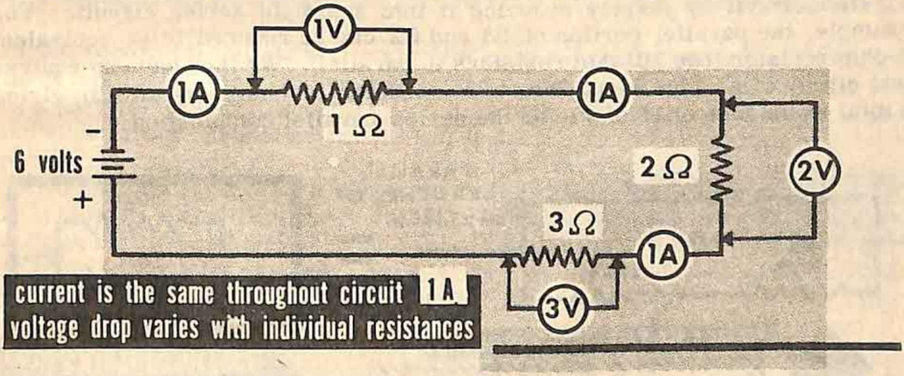


In our homes, each time we turn on an electrical device or appliance, we close a branch of a parallel circuit and draw additional current from our power supply (which are the power lines drawn into our homes by the electric utility company.) The utility company places a wattmeter in the incoming circuit to measure the total power consumed by the various devices in use. Every time a branch is closed, more current is drawn and more power used. As branches are opened, less power is consumed. Since the total current in a parallel circuit increases as additional branches are added, we see that the total resistance of a parallel circuit decreases as resistances are placed in parallel.

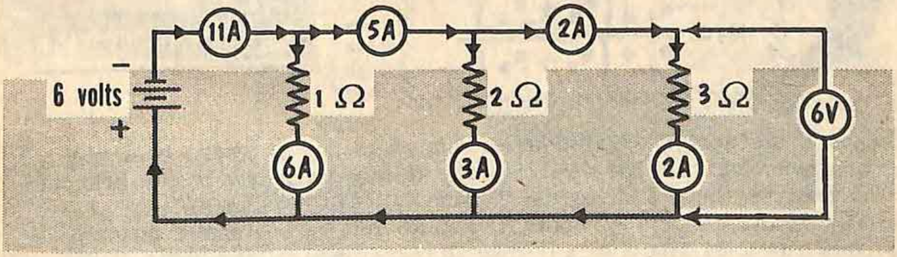
SUMMARY OF CHARACTERISTICS OF D-C CIRCUITS

SERIES CIRCUIT	PARALLEL CIRCUIT
1. The sum of the individual voltage drops equals the applied voltage.	The applied voltage is the same across each branch.
2. The total resistance is equal to the sum of the individual resistances that make up the circuit. $R_t = R1 + R2 + R3 + etc. \ldots$	The total resistance equals the reciprocal of the sum of the reciprocals of the resistances. Resultant resistance is less than the smallest resistance of the parallel combination.
3. Current is the same in all parts of the circuit.	The current divides in each branch according to the resistance of each branch.
4. Total power is equal to the sum of the power dissipated by the individual resistances.	(Same as series circuit) Total power is equal to the sum of the power dissipated by the individual resistances.

SERIES VS·PARALLEL CIRCUITS

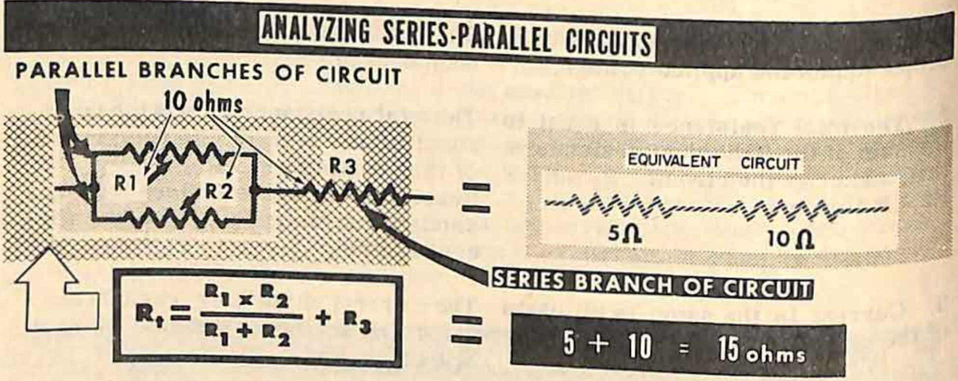


**current is the same throughout circuit 1A
voltage drop varies with individual resistances**

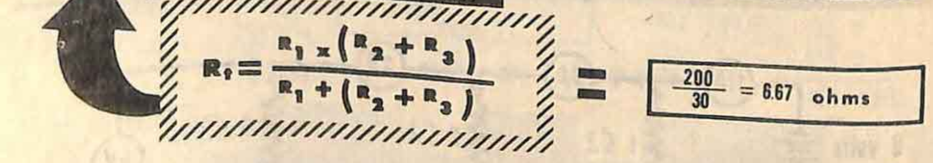


**voltage is constant across each branch (6 volts)
current in each branch varies with resistance of each branch**

Series-Parallel Circuits


ANALYZING SERIES-PARALLEL CIRCUITS
PARALLEL BRANCHES OF CIRCUIT
10 ohms
R1
R2
R3
EQUIVALENT CIRCUIT
5Ω
10Ω
SERIES BRANCH OF CIRCUIT
$R_t = \frac{R_1 \times R_2}{R_1 + R_2} + R_3$
5 + 10 = 15 ohms

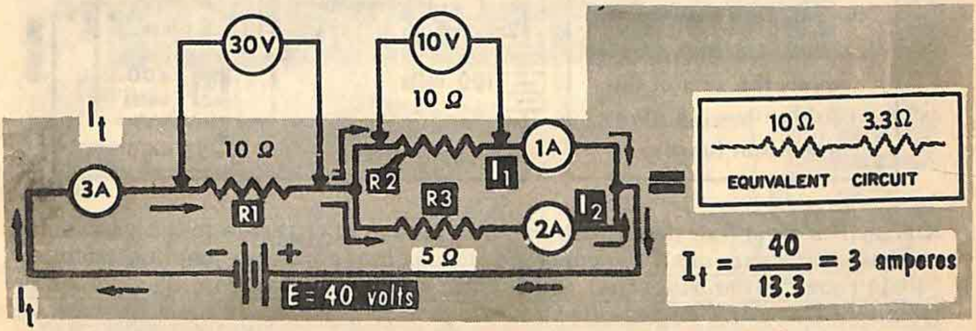
The third type of circuit arrangement is the series-parallel circuit. In this circuit, there is at least one resistance connected in series and two connected in parallel. The two basic arrangements of the series-parallel circuit are shown here. In one, resistors R1 and R2 are connected in parallel and this parallel connection, in turn, is connected in series with resistance R3. Thus, R1 and R2 form the parallel component, and R3 the series component of a series-parallel circuit. We can find the total resistance of any series-parallel circuit by merely reducing it into a simple series circuit. For example, the parallel portion of R1 and R2 can be reduced to an equivalent 5-ohm resistor (two 10-ohm resistors in parallel). We then have an equivalent circuit of a 5-ohm resistor in series with the 10-ohm resistor (R3), giving a total resistance of 15 ohms for the series-parallel combination.


PARALLEL BRANCHES OF CIRCUIT
R1 10Ω
R2 10Ω
R3 10Ω
10Ω
20Ω
EQUIVALENT CIRCUIT
SERIES BRANCH OF CIRCUIT
$R_t = \frac{R_1 \times (R_2 + R_3)}{R_1 + (R_2 + R_3)}$
$\frac{200}{30} = 6.67$ ohms

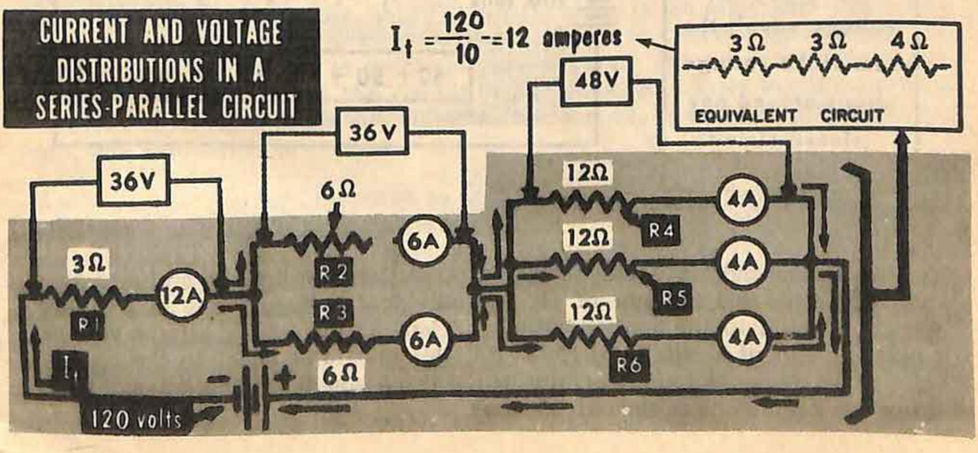
A second basic series-parallel arrangement is shown where basically we have two branches of a parallel circuit. However, in one of the branches we have two resistances in series. To find the total resistance of this series-parallel circuit, we first combine R2 and R3 into an equivalent 20-ohm resistance. The total resistance is then 20 ohms in parallel with 10 ohms, or 6.67 ohms. From these circuits, we see the basic scheme in solving series-parallel circuits: combine all series resistances and add them to the resistance of all parallel branches in the circuit.

Current and Voltage in Series-Parallel Circuits

In the series-parallel circuit shown, we see the distribution of current and voltage in such a circuit. Some things become quite apparent. For instance, since R2 and R3 are in parallel, the voltage across them would be the same. In addition, since R2 is twice the resistance of R3, the current flow through it would be only half as great as the current through R3. The current flow through R1 would be equal to the combined current through R2 and R3. Whenever the total current flows into a parallel branch, it splits up, with the greater amount flowing through the smaller resistor. The voltage drop, of course, across each branch of a parallel circuit would be equal.

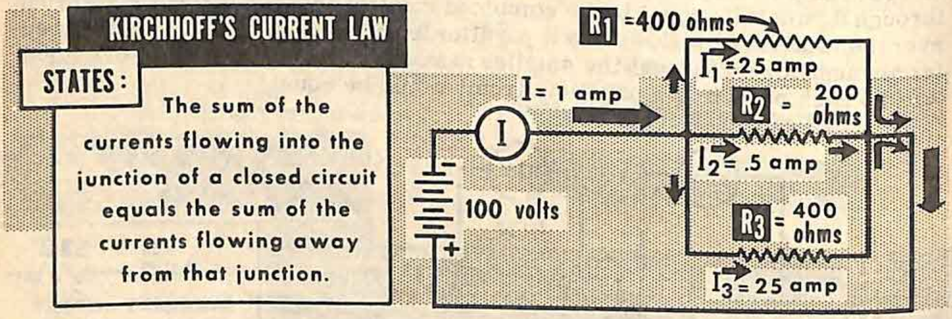


In the second circuit shown, we have a series-parallel circuit consisting of three sections. First, there is a series resistance R1. In series with this is a parallel branch R2 and R3 and, in series with this, is a three-branch parallel circuit consisting of R4, R5, and R6. The total current of 12 amperes flows through R1. It then breaks into two 6-ampere sections through R2-R3. Finally, it breaks into three 4-ampere sections through R4-R5-R6. Note that the voltage across each parallel section is equal to the IR or voltage drop in that section, and that the sum of the currents in each parallel section is equal to the total current. Keeping these general rules in mind, any kind of series-parallel circuit can be solved.

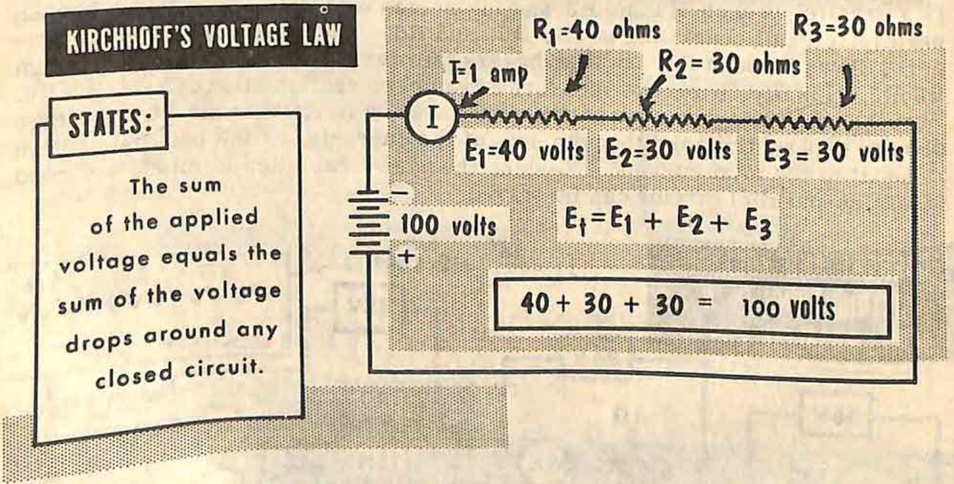

CURRENT AND VOLTAGE DISTRIBUTIONS IN A SERIES-PARALLEL CIRCUIT
$I_t = \frac{120}{10} = 12$ amperes
3 Ω
3 Ω
4 Ω
EQUIVALENT CIRCUIT
48V
36 V
36V
6 Ω
3 Ω
12A
6A
R2
R3
6A
6 Ω
R1
I_t
120 volts
12Ω
R4
12Ω
R5
12Ω
R6
4A
4A
4A

Kirchhoff's Laws

An interesting set of laws often used in circuit analysis are known as Kirchhoff's laws, named after Gustav Robert Kirchhoff (1824-1887). The principles they state have already been made known to you, although not as laws associated with a particular name.


KIRCHHOFF'S CURRENT LAW
STATES:
The sum of the currents flowing into the junction of a closed circuit equals the sum of the currents flowing away from that junction.
R1 =400 ohms
I1 =.25 amp
I= 1 amp
I
R2 = 200 ohms
I2 = .5 amp
100 volts
R3 = 400 ohms
I3 = 25 amp
-
+

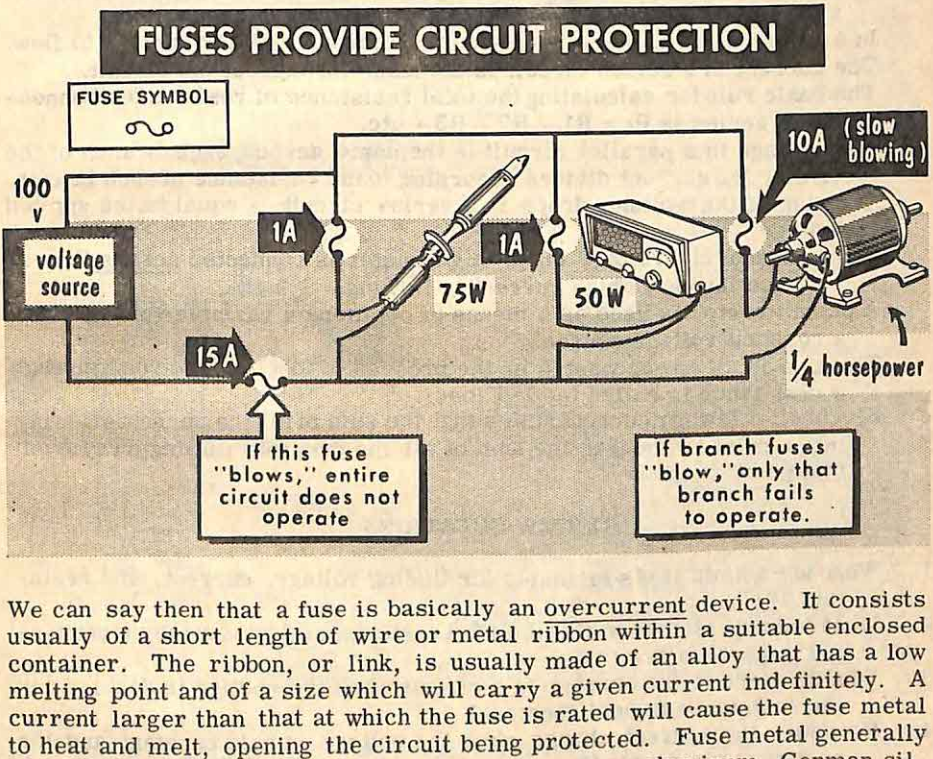
Kirchhoff's first law deals with the distribution of currents in a circuit. It states that the sum of all the currents flowing into a point or junction in a circuit is equal to the sum of all the currents flowing away from that point or junction. Thus, if 1 ampere flows into a junction, 1 ampere must flow away from that junction, whether in a single path or in many paths. In other words, current cannot accumulate anywhere in a circuit.



Kirchhoff's second law deals with the distribution of voltage in a closed circuit. It states that the sum of all the individual voltage drops in a closed circuit is equal to the applied voltage. Thus, if the sum of all the voltage drops in a circuit should total 100 volts, this should be equal to the applied voltage. If there is any difference in the two amounts, it indicates that an error has been made in the calculations.

Fuses

All electrical devices--soldering irons, motors, radios, etc., are designed to draw a certain amount of current when plugged into their rated voltage source. Occasionally, there is an electrical defect, the resistance of the electrical device falls off, and the amount of current drawn by the device increases greatly. This would cause the wires, often located inside walls, to overheat and possibly start a fire. To prevent such an occurrence, fuses are used. A fuse is connected in series with the electrical device it is to protect so that the total current flowing through the device will also flow through the fuse.


FUSES PROVIDE CIRCUIT PROTECTION
FUSE SYMBOL
100 V
voltage source
1A
75W
1A
50W
10A (slow blowing)
15A
¼ horsepower
If this fuse "blows," entire circuit does not operate
If branch fuses "blow," only that branch fails to operate.

We can say then that a fuse is basically an overcurrent device. It consists usually of a short length of wire or metal ribbon within a suitable enclosed container. The ribbon, or link, is usually made of an alloy that has a low melting point and of a size which will carry a given current indefinitely. A current larger than that at which the fuse is rated will cause the fuse metal to heat and melt, opening the circuit being protected. Fuse metal generally consists of an alloy of tin and bismuth, but copper, aluminum, German silver, and iron alloys are also used.

Fuses may be further classified as instantaneous or time-delay types. The instantaneous fuse carries its rated current indefinitely, but quickly melts when its rated current capacity is exceeded by about 25%. Time-delay fuses are designed to have a time delay for overloads. This feature is necessary to keep short-time surges (such as high starting currents for motors) from melting ("blowing") the fuse. This time delay permits momentary high current without damaging the fuse, while continuous excessive current produces a melted fuse. Some fuses are "sealed" and must be discarded when open; others have provisions for replacing the melted ribbon.

SUMMARY

Ohm's law defines the relationship between voltage, current, and resistance.

When resistance is held constant, current varies directly with voltage.

When voltage is held constant, current varies inversely with resistance.

Ohm's law for voltage is $E = IR$; for current, is $I = \frac{E}{R}$; for resistance, is $R = \frac{E}{I}$.

The unit used to express electrical power is the watt.

A watthour meter measures the amount of electrical power consumed.

Voltmeters measure voltage, ammeters measure current, ohmmeters measure resistance, and wattmeters measure power.

There are three basic types of electrical circuits: series, parallel, and series-parallel.

In a series circuit, there is only one continuous path for current to flow.

The current in a series circuit is the same throughout the circuit.

The basic rule for calculating the total resistance of resistances connected in series is $R_t = R1 + R2 + R3 +$ etc.

The voltage in a parallel circuit is the same across each branch of the circuit; the current divides according to the resistance of each branch.

The sum of the voltage drops in a series circuit is equal to the applied voltage.

When measuring voltage drop, a voltmeter is connected across the resistance through which current is flowing.

A potentiometer is used as a means of obtaining a variable voltage from a constant voltage source.

The amount of power wasted in the process of forcing electrons through a resistance is called the I^2R loss.

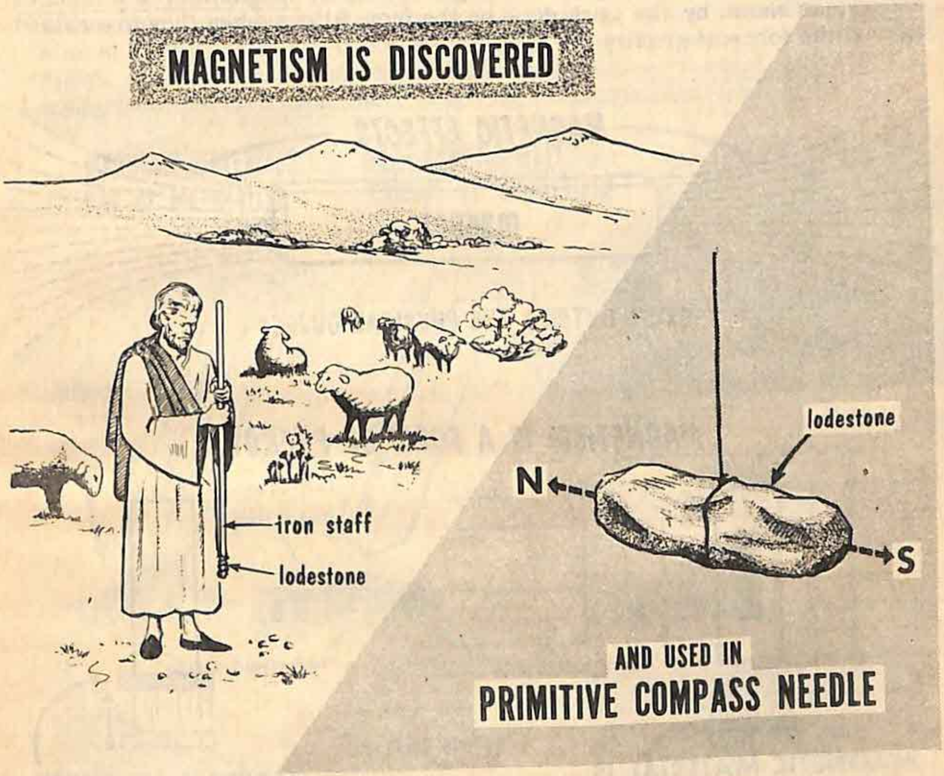
Kirchhoff's law for current states that the sum of all the currents flowing into a point is equal to the sum of all the currents flowing away from that point.

REVIEW QUESTIONS

1. What are Ohm's law's formulas for finding voltage, current, and resistance?
2. What formula is used to find the total resistance of two resistors connected in parallel?
3. What happens to the current in a circuit when the voltage is doubled and the resistance is held constant?
4. How does the current change when the voltage is held constant and the resistance is doubled?
5. What is the difference between current flow in a series circuit and in a parallel circuit?
6. How is a voltmeter connected when measuring voltage drop?
7. What voltage is required to light a 150-watt lamp drawing 3 amperes of current?
8. What is the wattage rating of a television receiver connected to a source of 120 volts and drawing 5 amperes?
9. How much power does an electric toaster consume if it operates from a source of 110 volts and draws 7.5 amperes?
10. What is the total resistance of a circuit having one 5-ohm and two 10-ohm resistors connected in parallel?

Magnetism and Electromagnetism

More than 20 centuries ago, an ore called magnetite was discovered The ancients called it "lodestone," or leading stone. It displayed the peculiar ability to attract tiny bits of iron to itself. Although the action was not understood, it was attributed to an invisible effect called magnetism, named after Magnesia, the area in ancient Greece where this type of "rock" was found. The lodestone, in turn, was given the related name of magnet.



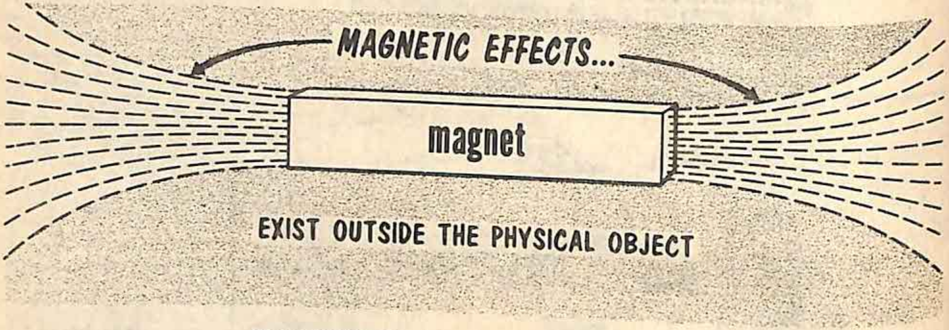
MAGNETISM IS DISCOVERED

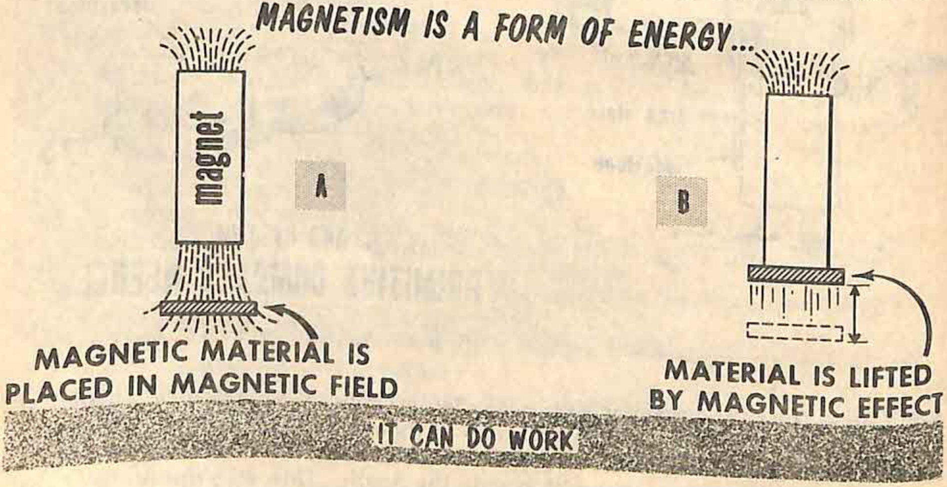
AND USED IN PRIMITIVE COMPASS NEEDLE

For a long time, the magnet was regarded merely as a curiosity. Then, it was discovered that if an elongated piece of lodestone was suspended horizontally so that it could turn freely, one end always pointed towards the North and the other end always pointed towards the South. This was the birth of the magnetic directional compass which has become invaluable to travelers on land, sea, and in the air. Much later it was found that the earth too behaved as a huge magnet; also, that the interaction between the magnetic effects of the magnet and that of the earth accounted for the "directional pointing" of the lodestone. It was concluded that what were called "magnetic effects" were the result of magnetic energy--magnetism was a form of energy that could do work. In time, it was realized that magnetism and electricity were related. It was found that effects associated with magnets could produce electric current in wires and that electric current gives rise to magnetic effects.

Magnetism Is a Form of Energy

If we sprinkle iron filings onto a sheet of paper and then hold a magnet slightly above the paper, filings will "leap" upward to the magnet. Iron filings are light and tiny, but as light as they may be, each filing is a physical entity and therefore, has some weight. The ability of whatever phenomenon is associated with the magnet to make the filings leap upward from the paper provides observable evidence of two conditions: first, magnetism exists outside of the physical body of the magnet; second, magnetism is a form of energy, as shown by the work done on the iron filings when they are raised against the force of gravity.

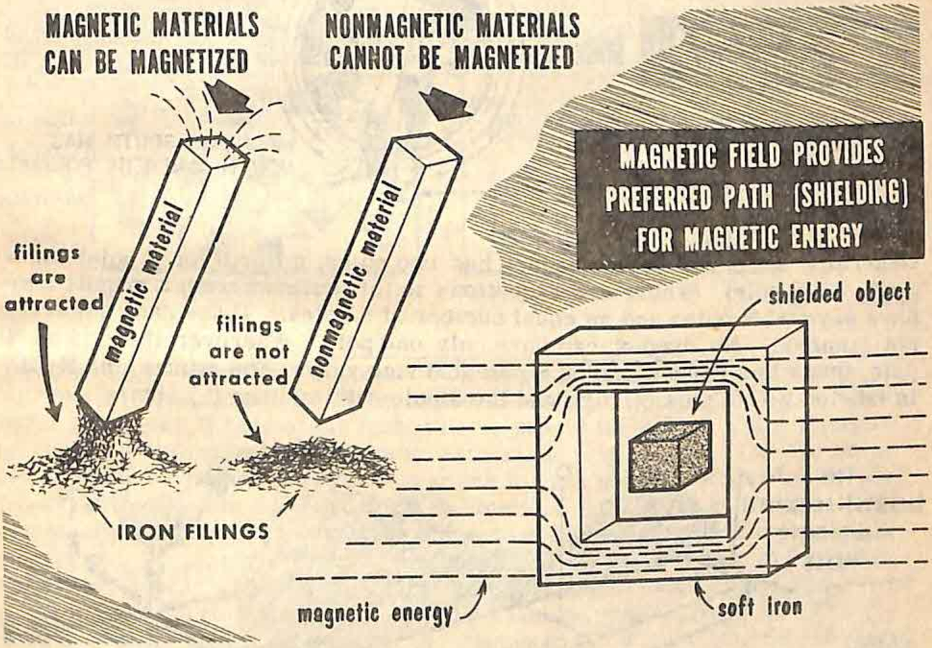

MAGNETIC EFFECTS...
magnet
EXIST OUTSIDE THE PHYSICAL OBJECT


MAGNETISM IS A FORM OF ENERGY...
magnet
A
B
MAGNETIC MATERIAL IS PLACED IN MAGNETIC FIELD
MATERIAL IS LIFTED BY MAGNETIC EFFECT
IT CAN DO WORK

Magnetic energy normally produces no response from the human senses. The area around the most powerful magnet is filled with magnetic energy, yet we cannot see, hear, taste, touch or smell it. We recognize its presence by its effects--magnetic effects. Magnetic energy can do much work. It can make another object, made of magnetizable material, into a magnet. Magnetic energy can raise very heavy objects made of magnetizable materials; it can exert mechanical force on other magnets; it contributes to the generation of emf by mechanical means; and it has many other applications.

Magnetic and Nonmagnetic Materials

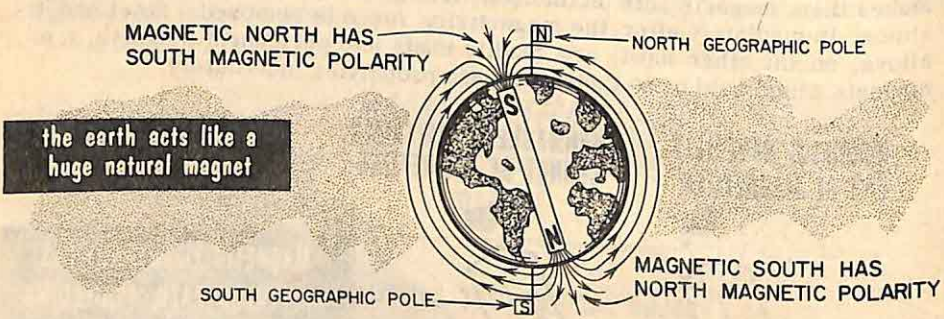
Magnetic materials can be magnetized and thus made to attract iron and certain other metals. Foremost among magnetic materials are soft iron and alloys of steel such as Alnico, containing one or more other metals including nickel, cobalt, and aluminum. Some recently developed "ceramics" make excellent magnets, among these being Indox, which contains barium-oxide and Vectolite, an iron-content compound. Temporary magnets are made from iron. They behave as magnets only as long as the magnetizing force which makes them magnets acts on the iron. Iron gives up its magnetic properties almost immediately after the magnetizing force is removed. Steel and its alloys, on the other hand, are readily made into permanent magnets; i. e., magnets which hold on to their magnetic properties indefinitely.


MAGNETIC MATERIALS CAN BE MAGNETIZED
NONMAGNETIC MATERIALS CANNOT BE MAGNETIZED
magnetic material
nonmagnetic material
filings are attracted
filings are not attracted
IRON FILINGS
MAGNETIC FIELD PROVIDES PREFERRED PATH (SHIELDING) FOR MAGNETIC ENERGY
shielded object
magnetic energy
soft iron

In contrast to the relatively few magnetic materials, there are a host of nonmagnetic materials; these cannot be magnetized. For our purposes, we need mention but a few: glass, paper, wood, rubber, plastic, cotton, tin, and copper. Although nonmagnetic materials cannot be magnetized, magnetic energy will pass through them; in fact, they are completely "transparent" to this kind of energy. Magnetic materials can be penetrated by magnetic energy also--but once inside the substance, the energy will use the material as a preferred path for as long as possible, rather than leave it and travel through air or through some other nonmagnetic substance. Thus, a magnetic substance is sort of a confining path for magnetic energy. It is this form of behavior that makes soft iron an excellent "shield" around an object from which we want to keep out magnetic energy.

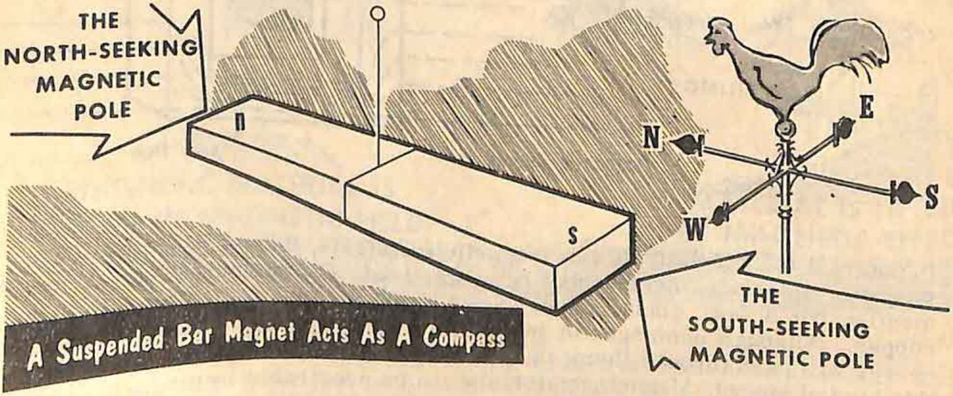
The Poles of a Magnet

If a permanent bar magnet is suspended horizontally so that it is free to rotate, it will come to rest with one end pointing towards the North pole of the earth, and the opposite end pointing towards the South pole. It has become conventional to refer to the ends of a magnet as the "poles" of the magnet, the end pointing towards the North being called the "north-seeking" pole, and conversely, the end pointing towards the South called the "south-seeking" pole.


MAGNETIC NORTH HAS SOUTH MAGNETIC POLARITY
N
NORTH GEOGRAPHIC POLE
S
N
MAGNETIC SOUTH HAS NORTH MAGNETIC POLARITY
SOUTH GEOGRAPHIC POLE
S

the earth acts like a huge natural magnet

Generally speaking, every magnet has two poles; a North (or N pole) and a South (or S pole). There are exceptions to this rule wherein a magnet may have several N poles and an equal number of S poles. These are, however, not common. No magnet can have only one pole. Wherever there is an N pole, there is a corresponding S pole and vice versa. Sometimes, the N pole is labeled with a plus (+) sign and the S pole with a minus (-) sign.

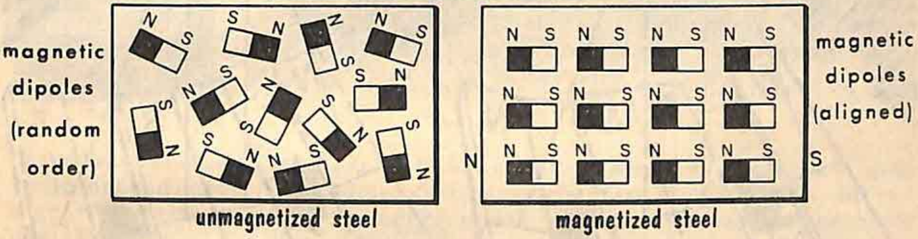

THE NORTH-SEEKING MAGNETIC POLE
N
S
N
E
W
S
THE SOUTH-SEEKING MAGNETIC POLE

A Suspended Bar Magnet Acts As A Compass

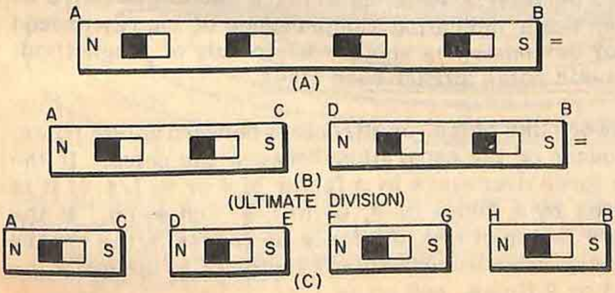
The earth behaves like a huge natural magnet, having a so-called North and South magnetic poles in the approximate direction (but not in the immediate vicinity) of their respective geographic poles. Based on the accepted behavior of a magnet and the laws of magnetism, the earth's North magnetic pole actually has south magnetic polarity, whereas the South magnetic pole actually has north magnetic polarity.

The Basis of Magnetism

How do we explain magnetism? The details are not exactly known but it is believed that magnetism is associated with the electrons in the atoms of which magnetic substances are made. These atoms are believed to be tiny magnets or "magnetic dipoles," each having a North pole and a South pole. Presumably, each atom accounts for a certain amount of magnetism, some more and some less. When a magnetizable material is in an unmagnetized state, the tiny atomic magnets are oriented in random fashion; that is, the magnetic poles point in all directions. When a substance contains randomly-oriented atomic magnets, it is assumed that the magnetic effects of one atom offset or cancel the magnetic effects of another. Thus, the material as a whole does not display any magnetic characteristics.


the dipole theory of magnetism

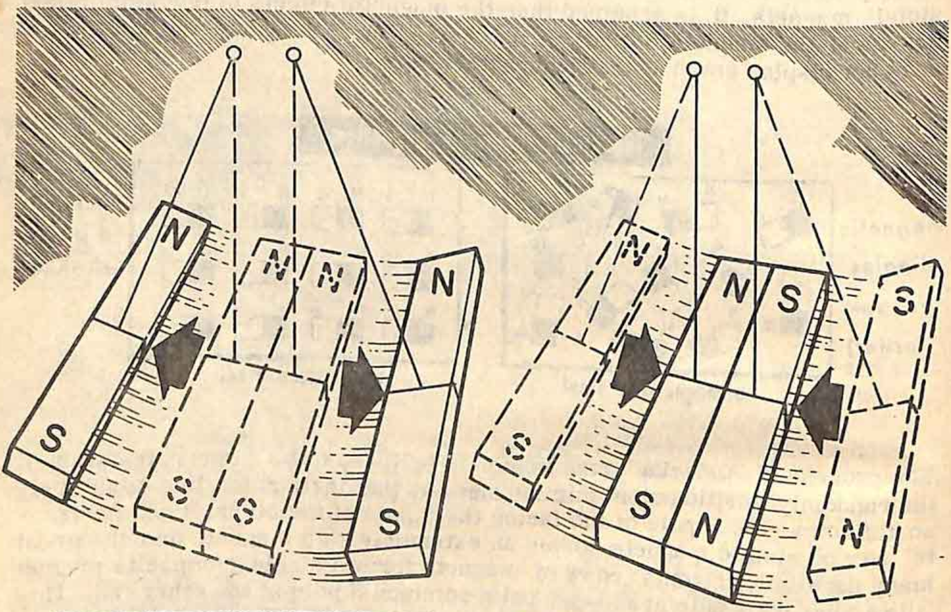
The process of "inducing" magnetism is believed to be the reorientation of the randomly-positioned atomic magnets so that their poles line up in horizontal rows--the N pole of one facing the S pole of the other. Each horizontal row of atomic magnets forms an extremely thin magnet, and the great many parallel horizontal rows of magnets form a single composite magnet with a common N pole at one end and a common S pole at the other end. This theory explains why it is possible to break a permanent magnet into any number of parts, each of which remains a magnet with an N and an S pole. When a material "loses" its magnetism, the atomic magnets change their "magnetized" orientation to a random one. In a permanent magnet, once it has been changed from random orientation to "magnetized" orientation, the atomic magnets in it stay that way until disrupted by heat or physical shock.



breaking a permanent magnet does not disturb the alignment of the magnetic dipoles

Attraction and Repulsion between the Poles of Magnets

Much of what is known about magnetism has been learned by experiment and observation of its effects. If we suspend two bar magnets with the two N poles (or S poles) near to and facing each other, a mutual force of repulsion is demonstrated between the like poles. The magnets move away from each other, indicating the presence of energy that can exert mechanical force. The action is described by a basic law of magnetism; namely, like magnetic poles repel each other.



LIKE MAGNETIC POLES REPEL EACH OTHER

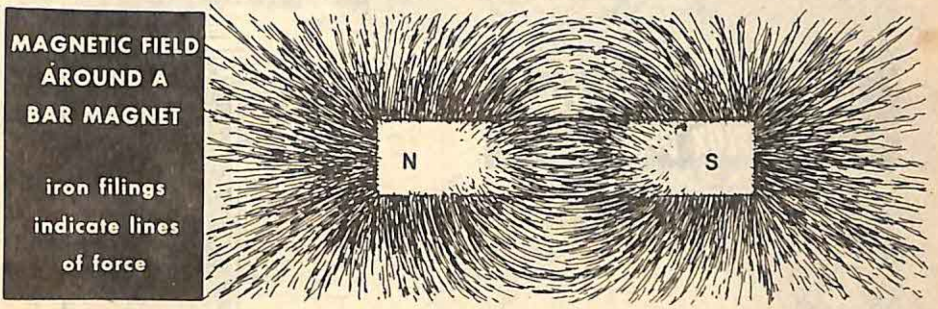
UNLIKE MAGNETIC POLES ATTRACT EACH OTHER

If the magnets are arranged so that the N pole of one faces the S pole of the other, the magnets will move towards each other. If the magnets are not perfectly in line, they turn on their axes so as to bring the unlike poles as close together as possible, again indicating the presence of energy around the magnet. Such behavior demonstrates another basic rule of magnetism, this being that unlike magnetic poles attract each other.

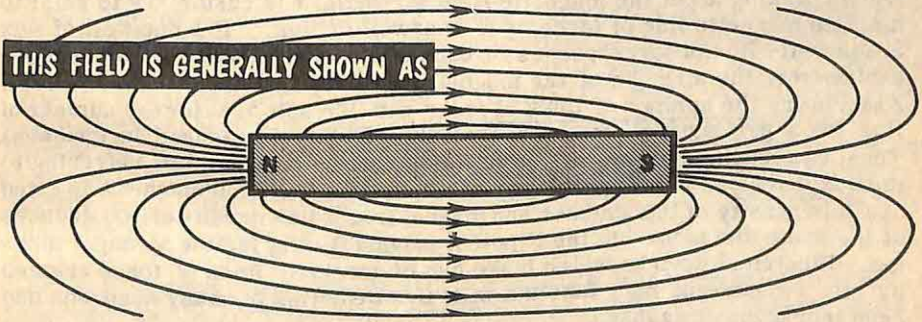
The force of repulsion between like poles, or attraction between unlike poles, varies inversely as the square of the separation between the poles. If the separation is doubled, the force decreases by a factor of 4 or to 1/4; if it is tripled, the force decreases by a factor of 9, or to 1/9, and so on. If the separation is decreased by a factor of two, the force increases by the square of 2 or 4 times; if the separation is decreased by a factor of 3, the force increases by the square of 3 or 9 times, and so on.

The Magnetic Field (Lines of Force)

How do we describe the energy around a magnet? Michael Faraday advanced the concept that the region in all directions around a magnet is a "zone of magnetic influence"; i. e., it is occupied by an invisible "magnetic field of force" or simply, a "magnetic field." Any magnetizable object placed within the magnetic field is made into a magnet--temporary or permanent, depending on the material--by the energy contained in the magnetic field.


MAGNETIC FIELD AROUND A BAR MAGNET
iron filings indicate lines of force
N
S

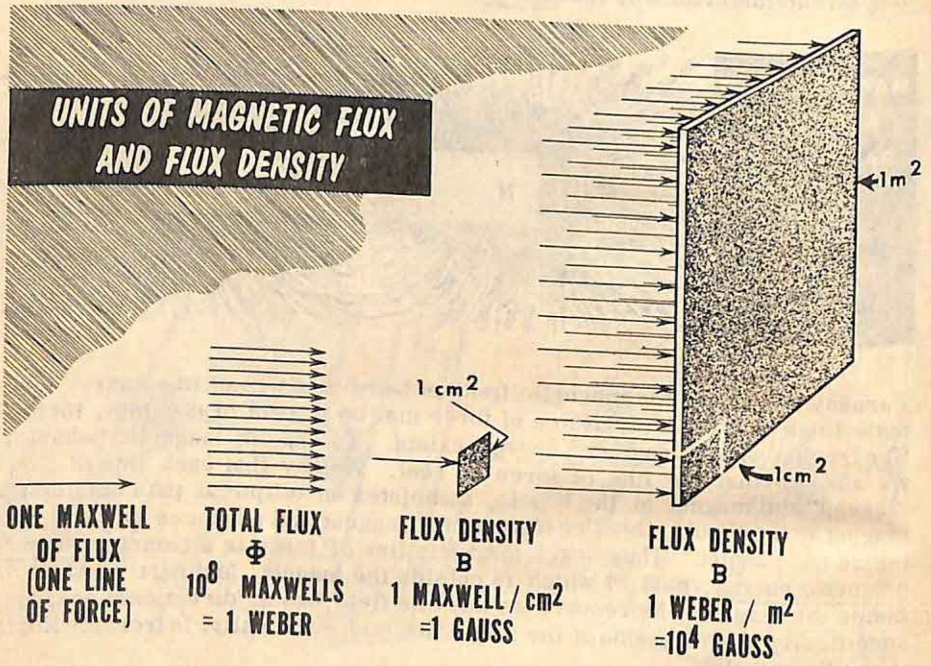
Faraday visualized the magnetic field as being made up of imaginary "magnetic lines of force." Each line of force may be thought of as a thin, thread-like region where magnetic energy exists. To explain magnetic behavior, we assume that the line of force is real. We say that each line of force "leaves" the magnet at the N pole, completes an elliptical path outside the magnet to the S pole, then "re-enters" the magnet and advances to the N pole inside the magnet. Thus, each magnetic line of force is a complete loop of magnetic energy, part of which is outside the magnet, and part of which is inside the magnet. Moreover, we say the field has a "directional quality." Specifically, the direction of the magnetic field, externally, is from the North to the South pole.



We can place a sheet of cardboard over a bar magnet, and sprinkle some fine iron filings. If we tap the cardboard lightly, the filings will arrange themselves in the "line" pattern shown. The pattern indicates the organization of the lines of force.

Lines of Force and Flux Density (Units)

To express the strength of the magnetic field at any given point around the magnet, or to compare the magnetic strength, we refer to the number of magnetic lines of force that pass through a unit area in the magnetic field. The unit area used for this purpose is a cross-section 1 centimeter on each side of 1 square centimeter (or 1 cm^2).

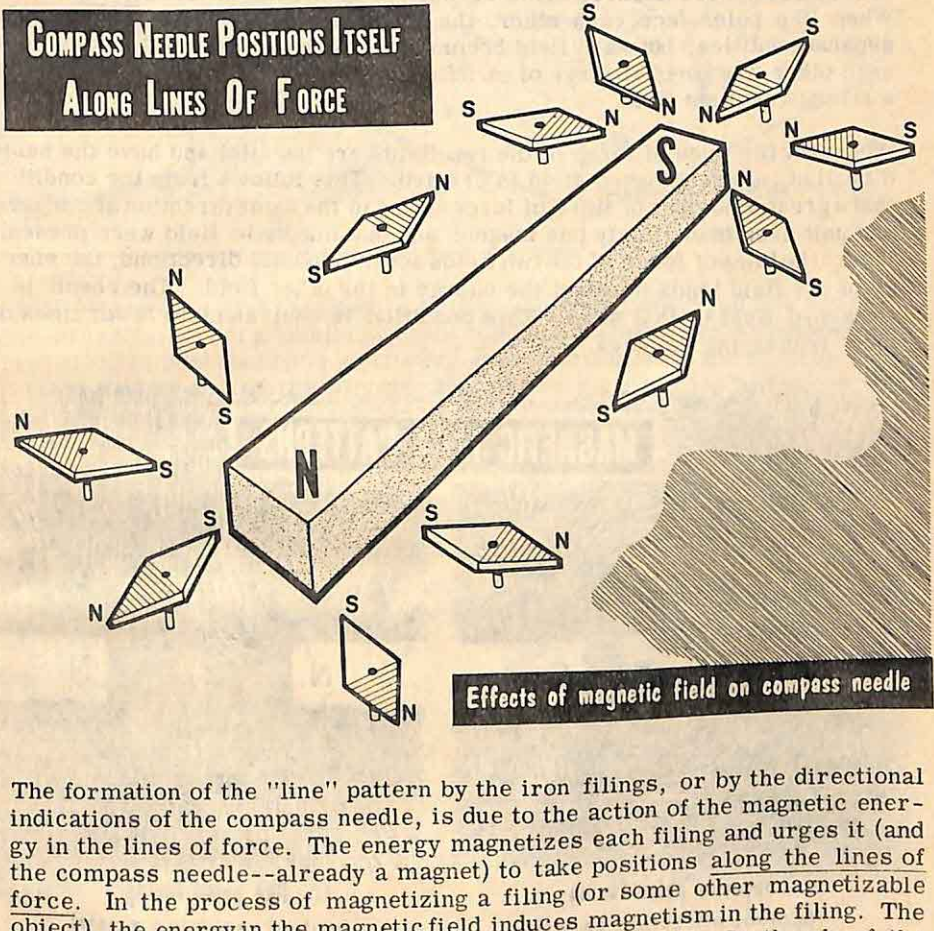

UNITS OF MAGNETIC FLUX AND FLUX DENSITY
1 m^2
1 cm^2
1 cm^2
ONE MAXWELL OF FLUX (ONE LINE OF FORCE)
TOTAL FLUX Φ 10^8 MAXWELLS = 1 WEBER
FLUX DENSITY B 1 MAXWELL / cm^2 =1 GAUSS
FLUX DENSITY B 1 WEBER / m^2 =10^4 GAUSS

When speaking about the magnetic field strength, it is customary to refer to a single magnetic line of force as a "maxwell of flux." If 1 maxwell of flux (1 magnetic line of force) passes through a cross-sectional area of 1 square centimeter, the strength of the magnetic field at that location is 1 gauss. Associating the number of lines of force with the unit area (or the number of flux lines per square cm) expresses flux density (measured in gausses). Thus, two magnets or two magnetic fields may be compared by referring to the flux density at corresponding points in the two fields. If magnet A is rated at a flux density of 100 gausses and magnet B at a flux density of 500 gausses at the same distance from the N poles, magnet B is by far the stronger magnet. Electrical devices which make use of magnetic lines of force created by electric current may function with flux densities of many hundreds and even thousands of gausses.

If reference is made to the total number of magnetic lines of force of a magnetic field, it is called total flux and is indicated by the symbol Ø. The unit used is 100,000,000 or 10^8 maxwells (lines of force). It is called "weber"; i. e., 10^8 maxwells = 1 weber.

Properties of Magnetic Lines of Force

Magnetic lines of force have numerous properties. Only two are discussed here; the rest are explained in connection with the magnetic effects of current.



COMPASS NEEDLE POSITIONS ITSELF ALONG LINES OF FORCE

Effects of magnetic field on compass needle

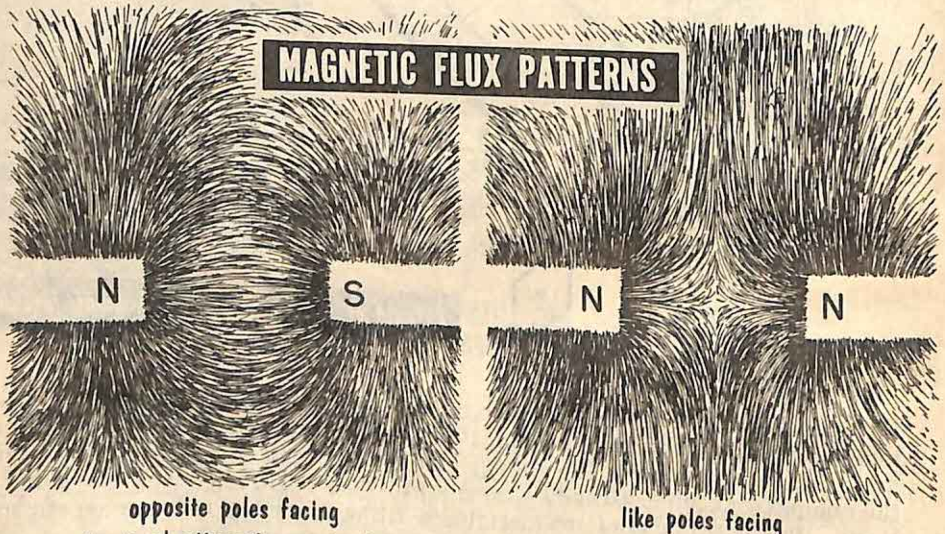
The formation of the "line" pattern by the iron filings, or by the directional indications of the compass needle, is due to the action of the magnetic energy in the lines of force. The energy magnetizes each filing and urges it (and the compass needle--already a magnet) to take positions along the lines of force. In the process of magnetizing a filing (or some other magnetizable object), the energy in the magnetic field induces magnetism in the filing. The end of the filing entered by the lines of force becomes the South pole of the magnetized bit of iron; the end where the lines of force leave the filing is the North pole. Thus, the magnetizing lines of force pass lengthwise through each magnet they create.

Being positioned along the lines of force, each tiny magnet in the field is threaded by the greatest number of flux lines. This is a rule of magnetic behavior. A magnetizable object located in a magnetic field will position itself so that it will be threaded by the greatest number of lines of force. Given sufficient energy in the magnetic field, the lines of force exert turning, pulling, or pushing force on other magnets on which they act, so that the magnets will be threaded by the greatest number of flux lines.

Properties of Magnetic Lines of Force (Cont'd)

Two magnets placed near each other have separate magnetic fields which occupy an area common to both. One might gather from this that the lines of force cross or intersect. This does not happen; lines of force never cross. When like poles face each other, the lines of force of each field remain separate entities, but each field becomes distorted. When unlike poles face each other, the lines of force of each field interact with the other and produce a strong resultant field.

Wherever the lines of force of the two fields are parallel and have the same direction, a strengthened field is created. This follows from the condition that a greater number of lines of force acting in the same direction are present per unit area than if only one magnet and one magnetic field were present. Where the lines of force of the two fields act in opposite directions, the energy of one field tends to offset the energy in the other field. The result is a weakened field in that area. This condition is equivalent to fewer lines of force traversing the area.



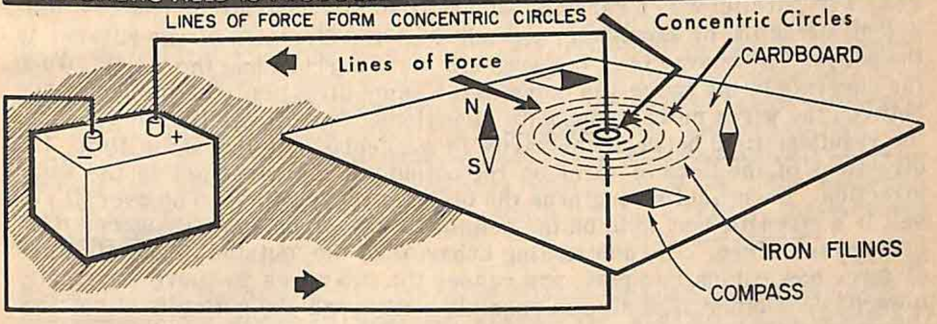
MAGNETIC FLUX PATTERNS

opposite poles facing
(mutual attraction exists)

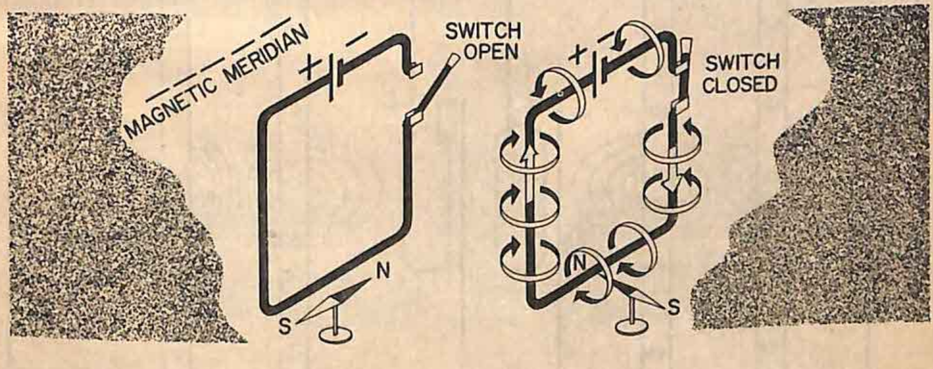
like poles facing
(mutual repulsion exists)

Still another important behavior of magnetic lines of force is that each magnetic loop behaves as though it were a rubber band stretched, which, if given the opportunity, would contract. This explains why unlike poles attract each other. The loops of magnetic force passing through the magnets behave as though they shrink, thus pulling the magnets toward each other. This is the simplified version of the condition whereby when one portion of a resultant of two fields is strengthened and another is weakened, the movable sources of the field move from the stronger to the weaker portion of the field. Strengthened and weakened magnetic fields in an area are illustrated by more or fewer lines of force.

Electromagnetism


MAGNETIC FIELD IS PRODUCED AROUND-CURRENT-CARRYING CONDUCTOR

In 1819, Hans Christian Oersted, a Danish physicist, observed that the directional indications of a small magnetic compass located near a wire through which electric current (d-c) was flowing were influenced by the current. The presence or absence of the current, as well as its direction of flow in the wire, had a major effect on the behavior of the compass needle. Later experiments by other scientists resulted in the conclusion that electric current produced a magnetic field or a zone of magnetic energy around itself. This was the beginning of electromagnetism, the term used to denote magnetic effects that result from electric current.

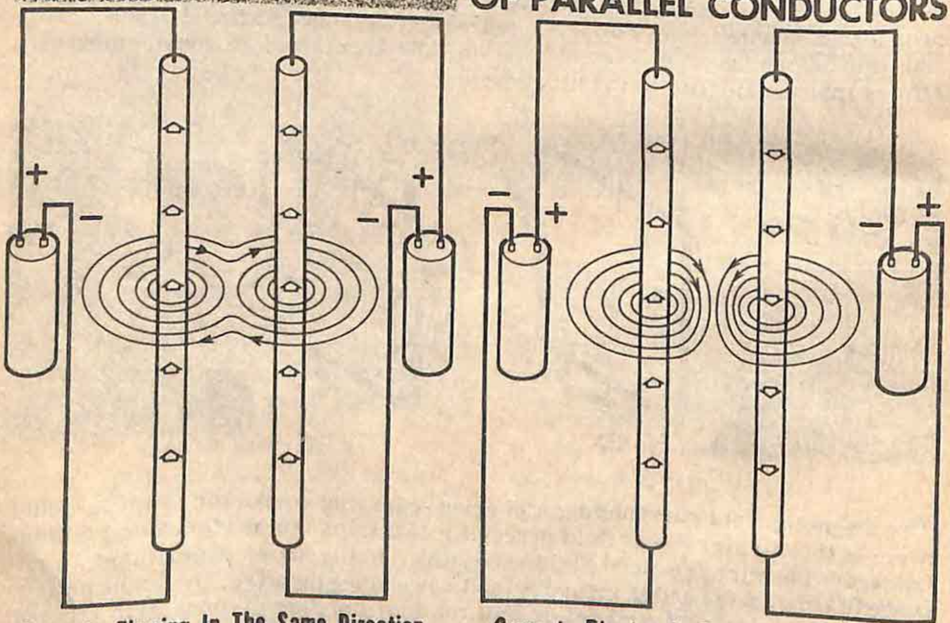


The magnetic field surrounding a current-carrying conductor is most dense nearest the wire (greatest field strength), and thins out at increasing distances from the wire (reduced field strength). If the above experiment is repeated as the cardboard is moved up and down along the wire, the same pattern appears at every point, indicating that the loops of force (concentric circles) surround the current all along its path. If a small compass is moved around the current-carrying conductor, the poles of the needle line themselves up with the magnetic lines of force and change their direction as the compass is moved around the wire. Thus, the lines of force created by the current have direction, just as the lines of force associated with a magnet have direction, except that the direction is now always at right angles (perpendicular) to the axis of the wire.

Action of Magnetic Field around Two Parallel Current-Carrying Wires

We showed that two magnets with facing poles demonstrate mechanical forces. Two parallel wires carrying current also demonstrate mechanical forces of attraction or repulsion, depending on the direction of the current in the wires. The energy is in the magnetic field surrounding the wires. When the currents in the two wires move in the same direction, the lines of force between the wires move in opposite directions. One offsets the other; hence, the resultant field between the wires is weakened. At the same time, the directions of the lines of force on the outside of the wires are in the same direction. Each field strengthens the other at these points. The overall result is a strengthened field on the outside of the wires and a weakened field between the wires. The contracting behavior of the "outside" magnetic lines of force now comes into play, and causes the two wires to move physically towards each other if motion is possible. Although the action is attraction between two wires, a much more useful description is to say that the strengthened portions of the field tend to push the conductors toward the weaker part of the field; hence, towards each other.

ACTION BETWEEN MAGNETIC FIELDS OF PARALLEL CONDUCTORS



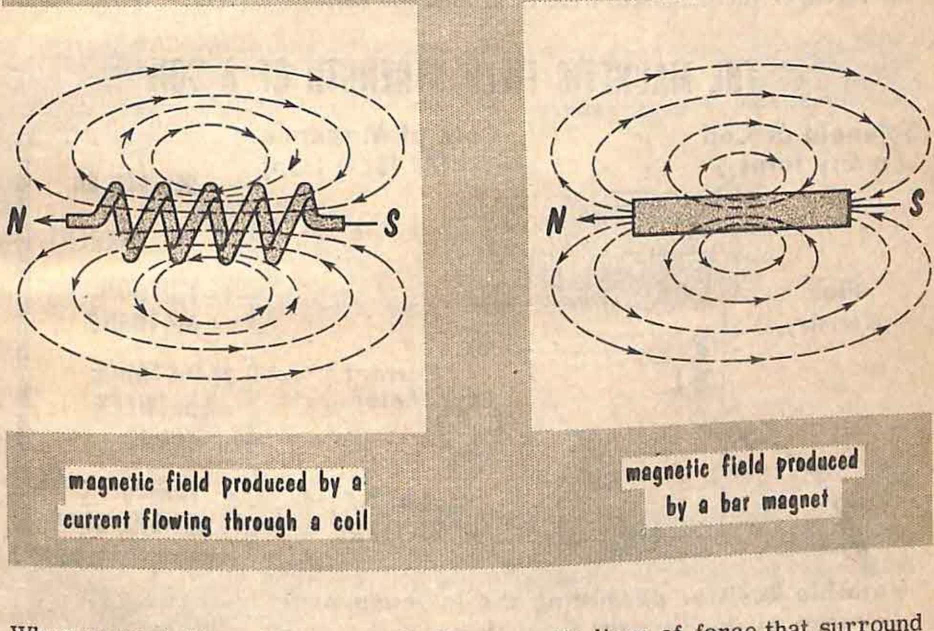
Currents Flowing In The Same Direction

Currents Flowing In The Opposite Direction

When the currents in the two parallel wires flow in opposite directions, the resultant field is strongest between the wires and weakest on the outside. The two wires therefore move apart, again moving from the stronger portion of the field (inside) towards the weaker portion (outside).

The Magnetic Field around a Current-Carrying Coil

When a straight conductor is bent into a series of loops, forming a coil (also known as a solenoid), a very much stronger magnetic field is created within the space inside the winding as well as outside the coil, but especially inside. The explanation is that each magnetic loop of force that encircles each turn passes through the inside of each turn--hence, through the inside of the coil as a whole--and all of them have the same direction. Because of this, the number of lines of force (or flux density) per unit area inside the coil is greater than anywhere else for the same area outside the turns. The magnetic field of a coiled wire is therefore very much stronger than if the wire had not been coiled.



COMPARISON OF MAGNETIC FIELDS

magnetic field produced by a current flowing through a coil

magnetic field produced by a bar magnet

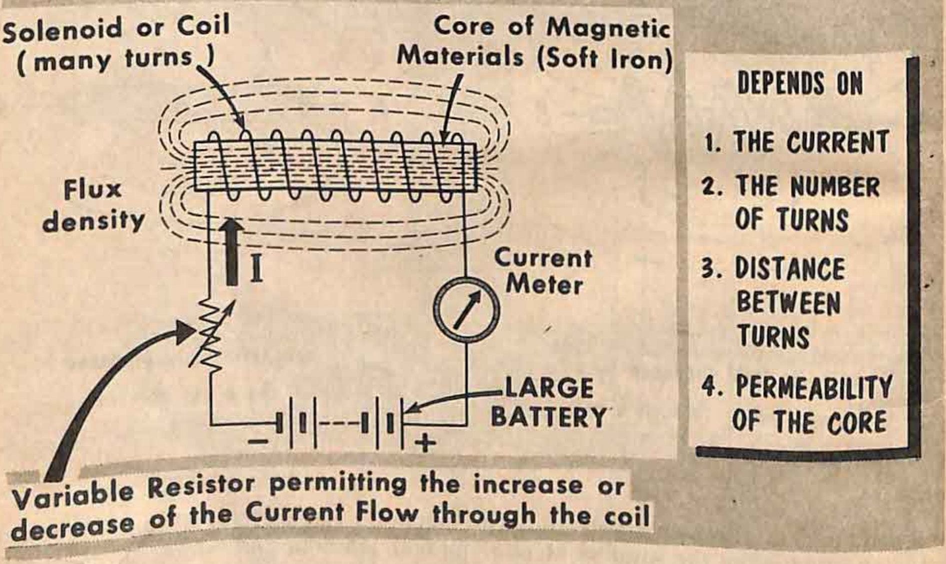
When current flows in a solenoid, the magnetic lines of force that surround the winding enter the winding at one end and leave at the other. Where the lines of force enter the winding is called the South end, or South pole, and the end where they leave is called the North end, or North pole. This organization of the magnetic field is like that of the conventional bar magnet; hence, a solenoid with current flowing in it is an electromagnet .

The term electromagnet denotes a magnet created by virtue of the magnetic lines of force that issue from an electric current. It is a "temporary" magnet because it behaves as such only while current is flowing in the wire. When the current ceases, the magnetic behavior ceases. Coils of few turns make weak magnets; to make them strong magnets requires many turns.

Strength of the Magnetic Field around a Solenoid (Ampere-Turns)

The strength of the magnetic field created by current in a solenoid is determined by several factors: the amount of current; the number of turns; the separation between the turns; and the core material. The more current there is in the winding, the greater the number of flux loops there are that surround the coil and the more energy there is in the magnetic field around the coil. Each turn through which current flows contributes lines of force to the total current; hence, the more the number of turns, the greater the number of flux loops everywhere around the coil. These two factors are combined into a single term called "ampere-turns." It is the product of the current in amperes and the number of turns. A coil with 100 turns and .5 ampere of current has the same ampere-turns as a coil with 500 turns and 1 ampere of current, for $100 \times .5 = 500 \times .1$. The closer the turns are to each other, the greater the linkage between the flux lines; i. e., the more readily the flux loops around the individual turns link with other turns, and the stronger the magnetic field is around the coil.

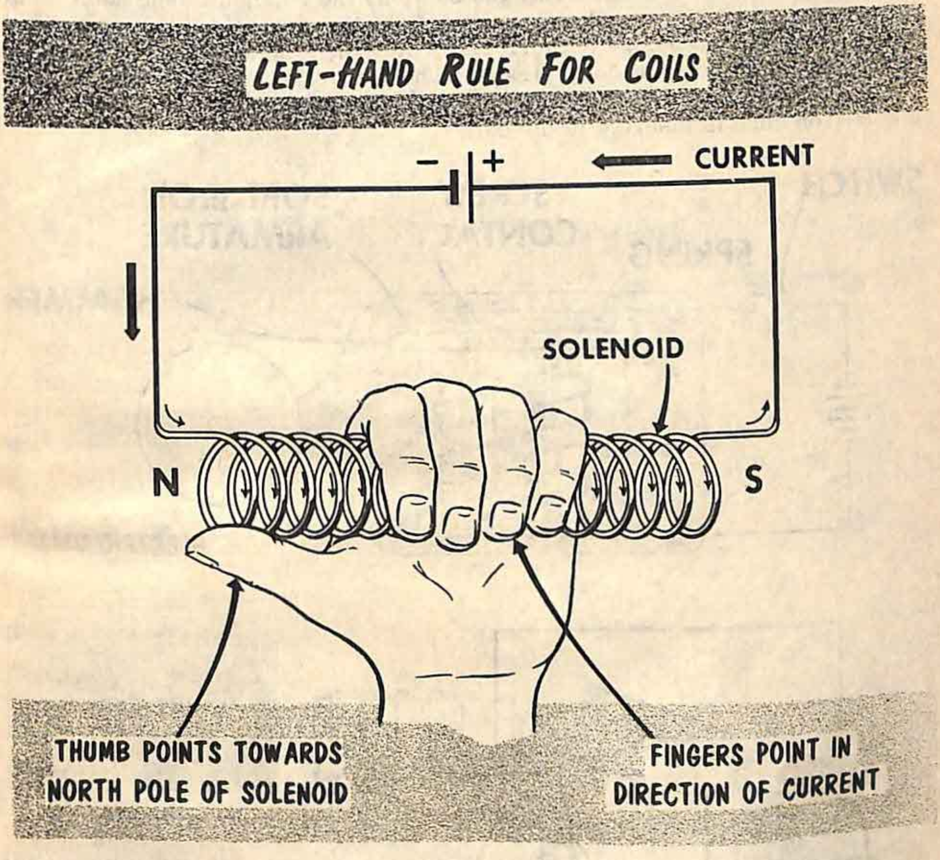
THE MAGNETIC FIELD STRENGTH OF A COIL


Solenoid or Coil (many turns)
Core of Magnetic Materials (Soft Iron)
Flux density
I
Current Meter
LARGE BATTERY
−
+
Variable Resistor permitting the increase or decrease of the Current Flow through the coil
DEPENDS ON
1. THE CURRENT
2. THE NUMBER OF TURNS
3. DISTANCE BETWEEN TURNS
4. PERMEABILITY OF THE CORE

A coil wound on an insulated form with an air-filled core will, for a given current, have a weaker magnetic field than a coil wound on a core made of a magnetizable material such as soft iron. The soft iron core becomes magnetized and, in this state, creates additional lines of force which add to the total due to the current. The core material is described in terms of its permeability or magnetic conductivity. Permeability expresses the ease with which magnetic lines of force are established in a material relative to that in air or in a vacuum, both of which have a permeability of 1. Magnetic materials with a permeability exceeding 50,000 are available.

The Left-Hand Rule for a Coil

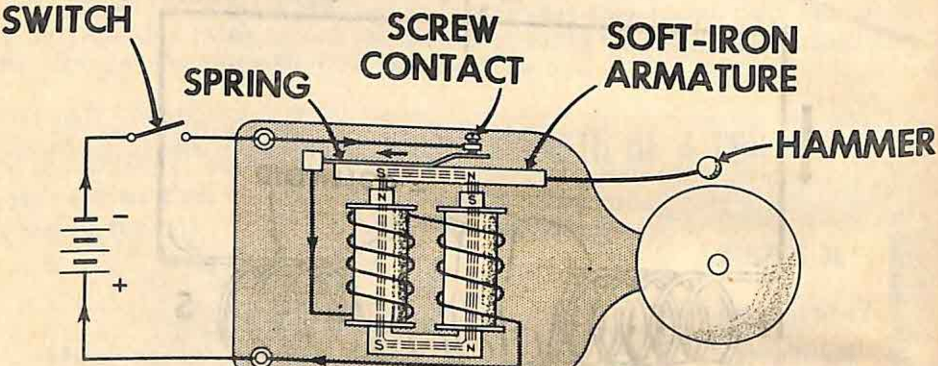
The magnetic polarity produced by the flow of current through a coil is determined by the direction of the current and the direction of the coil winding. We should not confuse the voltage drop across a coil with the polarity magnetic produced in the coil. North and South are terms applied to opposite magnetic poles; minus and plus are terms used to describe a difference of potential.


LEFT-HAND RULE FOR COILS
−
+
CURRENT
SOLENOID
N
S
THUMB POINTS TOWARDS NORTH POLE OF SOLENOID
FINGERS POINT IN DIRECTION OF CURRENT

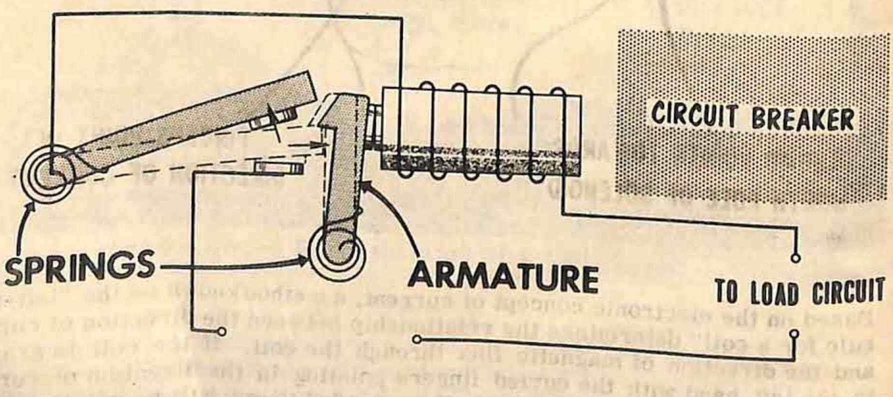
Based on the electronic concept of current, a method known as the "left-hand rule for a coil" determines the relationship between the direction of current and the direction of magnetic flux through the coil. If the coil is grasped in the left hand with the curled fingers pointing in the direction of current flow through the turns of the coil, the extended thumb will be pointing in the direction of the flux and the North pole of the coil. Obviously, the other end of the coil is then the South end, or South "pole." As you will see later, the interaction between the magnetic field that surrounds a conductor in which current is flowing and a permanent magnetic field that exists between magnetic poles is the basis for operation of a wide variety of electrical devices.

The Electromagnet

No other electromechanical device is so widely used or representative of magnetism and electricity as the electromagnet. This unit is composed of a coil or wire wound around a soft iron core. When direct current flows through the coil, the core becomes magnetized with the same polarity that the coil (or solenoid) would have taken without the iron core. When the current through the coil is reversed, the polarity of the electromagnet is reversed. The polarity follows the left-hand rule the same as the solenoid. The addition of the soft-iron cores serves two functions: first the magnetic flux is increased because the soft-iron core is more permeable than the air core; second, the flux is much more highly concentrated. The permeability of soft iron is many times that of air; therefore, the flux density is increased considerably when a soft-iron core is inserted in the coil.



ELECTRIC BELL



CIRCUIT BREAKER

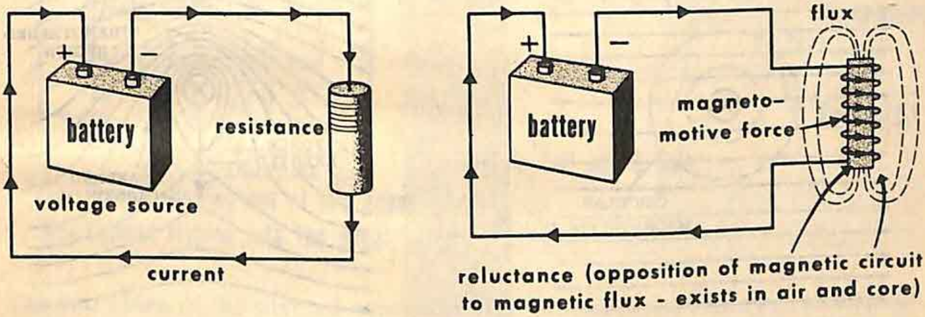
Popular applications of the electromagnet are in bells and buzzers, in circuit breakers used to protect circuits, and in relays, used to open and close circuits. Note that in the devices shown, the fundamental operation depends upon the electromagnet becoming energized and attracting a movable piece of metal called an armature.

The Magnetic Circuit

Lines of magnetic flux do not end at magnetic poles, but are continuous or closed on themselves like the lines of electron flow in an electric circuit. In fact, a magnetic circuit is, in many ways, similar to an electric circuit. To produce an electric current, a voltage called an electromotive force is required. Similarly, to produce a magnetic flux, a force called a magnetomotive force is required. In an electric circuit, for a given amount of voltage or electromotive force, the current is determined by the circuit resistance. Similarly, in a magnetic circuit, for a given amount of magnetomotive force, the flux density depends upon the amount of opposition or reluctance. Thus, in the magnetic circuit, as in the electric circuit, we can say: the result produced is directly proportional to the force that produces it and inversely proportional to the opposition encountered.

COMPARING THE ELECTRIC AND MAGNETIC CIRCUIT

$$I \text{ (current)} = \frac{E \text{ (electromotive force)}}{R \text{ (resistance)}} \qquad \emptyset \text{ (flux or lines of force)} = \frac{F \text{ (magnetomotive force)}}{R \text{ (reluctance)}}$$

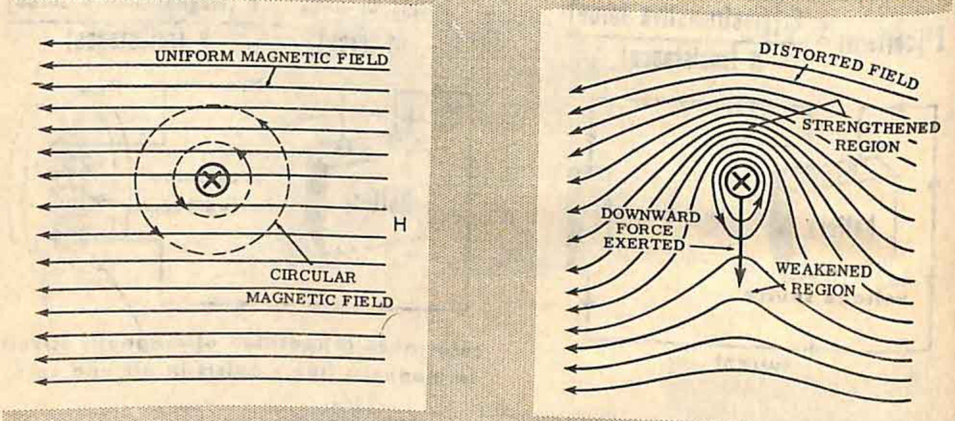

+
−
battery
resistance
voltage source
current
+
−
battery
flux
magneto-
motive force
reluctance (opposition of magnetic circuit to magnetic flux - exists in air and core)

There are two important differences in the relationship of the electric circuit to that of the magnetic circuit. The first difference is that in the electric circuit, the resistance is a constant value and can be determined by measuring the ratio of voltage to current. In a magnetic circuit, however, the reluctance is not a constant but depends upon the flux, or field strength. The second difference is that in electric circuits, current actually flows (electron flow) from one point to another. In the magnetic circuit, there is no actual flow of flux, but merely an indication of the intensity and direction of the magnetic field.

The magnetizing force set up due to current flowing in a coil or solenoid is known as the magnetomotive force (abbreviated mmf). The practical unit of magnetomotive force is the ampere-turn. We can then say that the magnetomotive force is proportional to the current (in amperes) in the circuit and to the number of turns of the coil. The magnetic flux ($\emptyset$) comprises the total number of lines of force in the magnetic circuit. The maxwell is the unit of flux (1 line of force is equal to 1 maxwell).

Motion of a Current-Carrying Conductor in a Magnetic Field

You have learned that a current in a conductor is surrounded by a magnetic field. If this conductor is placed within a stationary magnetic field, the two fields combine to produce a single resultant distorted field which exerts force on the conductor. The force is attributable to the creation of a strengthened and a weakened region in the resultant field around the conductor. For instance, the lines of force of the individual fields have the same direction above the wire; hence, a strengthened field is created above the wire. Below the wire, the field produced by the current has a direction which is opposite to the field of the magnets, so the two fields buck each other and create a weakened region. The conductor will be moved downward because it is "pushed" from the strengthened region to the weakened region of the field.



MOTION OF A CURRENT-CARRYING CONDUCTOR PLACED IN A MAGNETIC FIELD

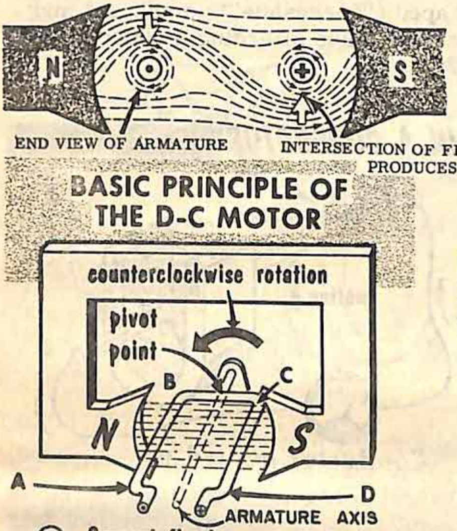
CIRCULAR MAGNETIC FIELD SUPERIMPOSED ON UNIFORM MAGNETIC FIELD

RESULTANT OF THE TWO SUPERIMPOSED FIELDS

By changing the direction of the current in the wire, we can transpose the locations of the strengthened and weakened regions of the resultant field around the wire. The former is now located below the wire and the latter above it. The wire now is "pushed" upward. The greater the amount of current in the wire, the stronger are the aiding and bucking effects; therefore, the greater the difference in magnitude of the strengthened and the weakened parts of the field. This results in greater force being exerted on the wire and more rapid motion. The foregoing description explains a fundamental condition which has many applications. Two prominent ones are related to the electric motor and the "moving-coil" type of electric meter. Both are discussed in more detail on the pages to follow.

The D-C Motor

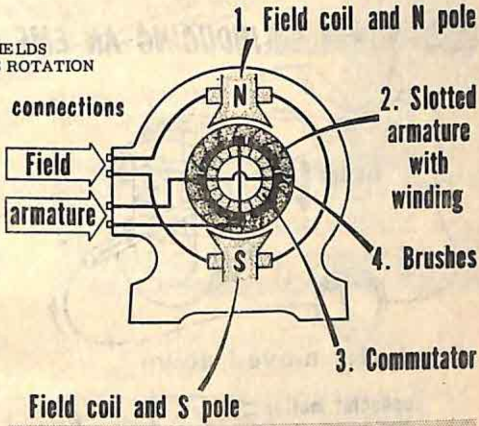
A d-c motor is a rotating machine that transforms electrical energy into mechanical energy. The basic principle was explained on the preceding page. The stationary magnetic field can be created by a d-c current in a winding on a suitably-shaped core of soft iron, as well as by the use of a permanent magnet.


N
S
END VIEW OF ARMATURE
INTERSECTION OF FIELDS PRODUCES ROTATION
BASIC PRINCIPLE OF THE D-C MOTOR
counterclockwise rotation
pivot point
B
C
N
S
A
D
ARMATURE AXIS

⊙—Current flowing out of the paper

⊕—Current flowing into the paper

THE FOUR MAJOR COMPONENTS OF A D-C MOTOR ARE:



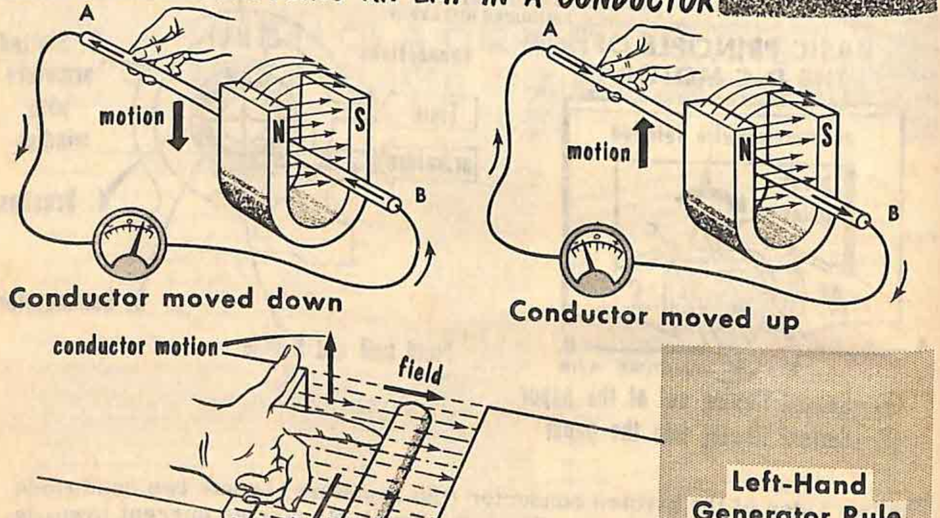
The two sides of the pivoted conductor (the armature) create two conditions of current direction within it. The left side (A-B) carries current towards the reader, whereas the right side (C-D) carries current away from the reader. Side B-C is just a conducting link. The magnetic field of the current in side A-B, acting in conjunction with the stationary field of the magnet, causes the resultant field to be stronger above the conductor and weaker below it. In the case of the right side, C-D, the direction of the current causes the resultant field to be stronger below the conductor and weaker above it. Thus, a downward push is felt by A-B and an upward push by C-D. With the loop of wire pivoted at two points, the mechanical forces produce a torque (a force which tends to turn things), causing rotary motion on the part of the loop as a whole.

The practical motor has many turns for the armature. Physically, it consists of a soft steel frame with slots into which the turns are wound. The turns are divided into separate groups which terminate on the commutator, a device used for making electrical contact with the conducting loops as they rotate. The commutator and brushes enable the current always to be passed into those turns which face the pole pieces, thereby generating continuous torque to keep the armature rotating.

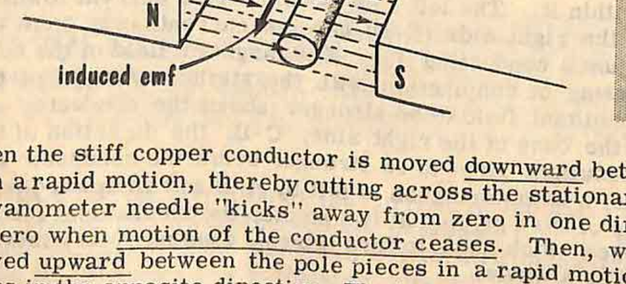
Induced Electromotive Force (emf) ; Moving Conductor Generator

In the d-c motor, electrical energy is transformed into mechanical energy by making use of magnetic effects. The reverse is also true; mechanical energy can be transformed into electrical energy by utilizing magnetic effects. This occurs in the electric generator. A simple experiment demonstrates the process. A short length of stiff copper wire is connected to a sensitive zero-center galvanometer by means of two lengths of flexible copper wire. Also required is a strong "U"-shaped ("horseshoe") permanent magnet with pole pieces which are close together, thus affording a concentrated stationary magnetic field between them.

INDUCING AN EMF IN A CONDUCTOR



Conductor moved down **Conductor moved up**

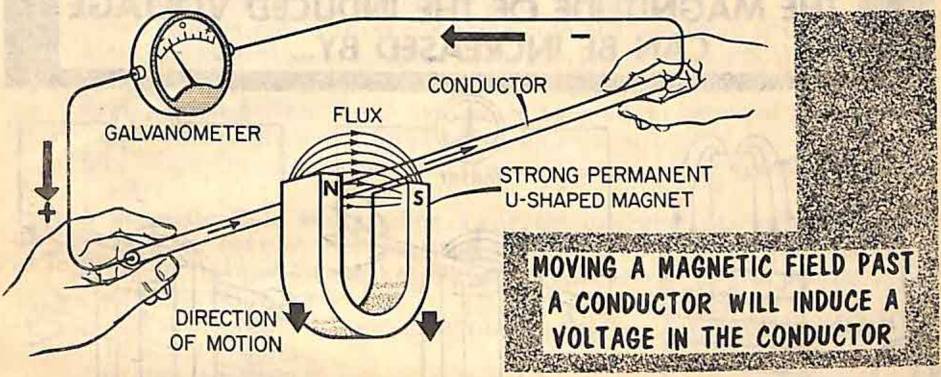


Left-Hand Generator Rule

When the stiff copper conductor is moved downward between the pole pieces with a rapid motion, thereby cutting across the stationary lines of force, the galvanometer needle "kicks" away from zero in one direction, and returns to zero when motion of the conductor ceases. Then, when the conductor is moved upward between the pole pieces in a rapid motion, the meter needle kicks in the opposite direction. The two directions of deflection of the needle indicate current flow in opposite directions. Both are the result of an electromotive force (voltage) being induced in the stiff copper wire while it is cutting across the magnetic lines of force between the pole pieces. If the wire is moved horizontally (i. e., parallel to the lines of force in either direction between the pole pieces), no current is evident on the galvanometer. The overall action is described by saying that "when a conductor cuts magnetic lines of force, an electromotive force is induced in the conductor."

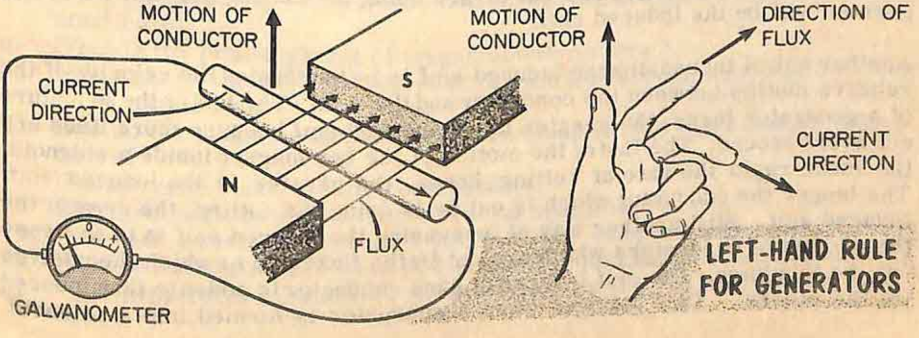
Induced Electromotive Force; Moving Magnetic Field

Instead of moving the conductor so that it will cut stationary magnetic lines of force, we reverse the process and move the magnetic field so that moving lines of force cut the stationary conductor. As with the case of the moving conductor, maximum emf is induced when the lines of force cut the conductor at right angles, and minimum emf (effectively zero) is induced when the moving lines of force have a direction parallel to the axis of the conductor.



MOVING A MAGNETIC FIELD PAST A CONDUCTOR WILL INDUCE A VOLTAGE IN THE CONDUCTOR

The electrical polarity of the voltage induced in the conductor, hence, the direction of the resultant current in the galvanometer circuit, is a function of the relative direction of motion between the moving magnetic lines of force and the stationary conductor. When the magnetic field moves downward, it is the same as though the conductor moves upward. When the magnetic field moves upward, it is the same as though the conductor moves downward through the field. As to the polarity of the voltage induced in the conductor by the relative motion between the conductor and the magnetic lines of force, it is indicated by the "left-hand rule for generators." This rule states that if you hold the thumb, first and middle fingers of the left hand at right angles to one another, with the first finger pointing in the direction of the lines of force and the thumb pointing in the direction of motion of the conductor, then the middle finger will point in the direction of the induced emf (the direction in which current will flow).

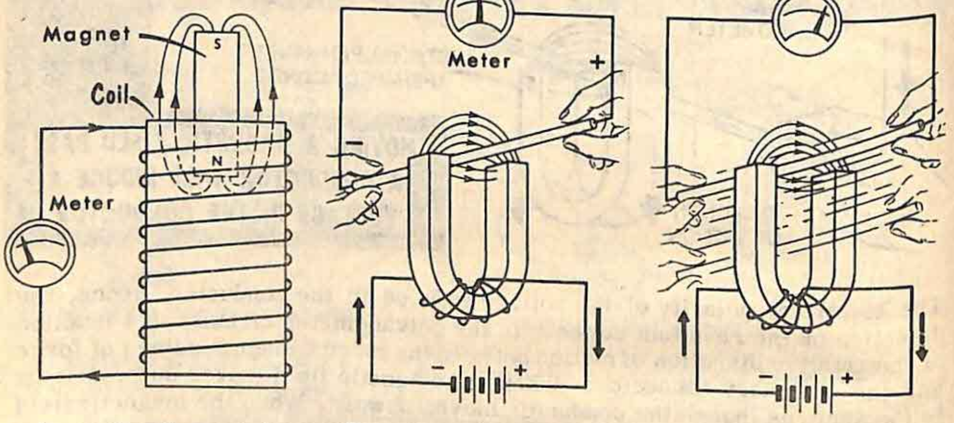


LEFT-HAND RULE FOR GENERATORS

Factors That Control the Amount of Induced EMF

The amount (magnitude) of the emf (voltage) induced by relative motion between magnetic lines of force and a conductor is determined by several factors. In this connection, do not try to associate every magnetic field with a permanent magnet; think just of the magnetic field regardless of its origin.

THE MAGNITUDE OF THE INDUCED VOLTAGE CAN BE INCREASED BY...



1 winding the conductor to form a coil of many turns

2 replacing the magnet with a strong electromagnet

3 increasing the relative speed of the movement between conductor and field

The angular relationship between the magnetic lines of force and the conductor already has been mentioned. Another is the strength of the magnetic field which is cut, or which is doing the cutting. The greater the field strength (that is, the greater the flux density), or the more the number of lines of force per unit area which are cut or are doing the cutting per unit time, the greater will be the induced emf.

Another way of increasing the induced emf is by increasing the velocity of the relative motion between the conductor and the field. The faster the armature of a generator turns, the greater is the induced emf because more lines are cut every second. The faster the motion of the bar magnet inside a solenoid, the more rapid the rate of cutting; hence, the greater is the induced emf. The longer the conductor which is cut or is doing the cutting, the greater the induced emf. Still another way of increasing the induced emf is to increase the number of conductors which are cut by the flux lines or which themselves cut the flux lines. The emf induced in each conductor is added to that induced in the others. This happens when a conductor is formed into a solenoid.

Pieces of iron ore called magnetite were found to possess magnetic properties which attracted bits of iron. These natural magnets were called lodestones.

Any magnet that retains its magnetism over a long period of time is a permanent magnet; if it loses its magnetism rapidly, it is a temporary magnet.

The space surrounding a magnet is called a magnetic field. Magnetic lines of force are concentrated around the poles of a magnet.

Pieces of iron or steel become magnetized by induction when they are brought close to, or in contact with, a magnet.

Every magnet has at least one north pole and one south pole.

Artificial magnets can be made by stroking an unmagnetized piece of iron or steel with a magnet, or by electrical means.

Residual magnetism is the amount of magnetism retained in a material after the magnetizing force has been removed.

Like magnetic poles repel each other; unlike magnetic poles attract each other.

A magnetic field surrounding a current-carrying conductor increases when the current increases and decreases when the current decreases.

Magnetic lines of force take the form of concentric circles around a current-carrying conductor.

A coil through which current is flowing has two polarity identities--voltage and magnetic.

The "left-hand rule" for a coil determines the relationship between the direction of current and the direction of magnetic flux through the coil.

Ampere-turns is the product of the current in amperes and the number of turns of the coil. Magnetomotive force is expressed in ampere-turns.

An electromagnet is composed of a coil or wire wound around a soft iron core.

The maxwell is the unit of magnetic flux; 1 line of force is equal to 1 maxwell.

When the current through the coil of an electromagnet is reversed, the polarity of the electromagnet is reversed.

Moving a magnetic field past a conductor will induce a voltage in the conductor.

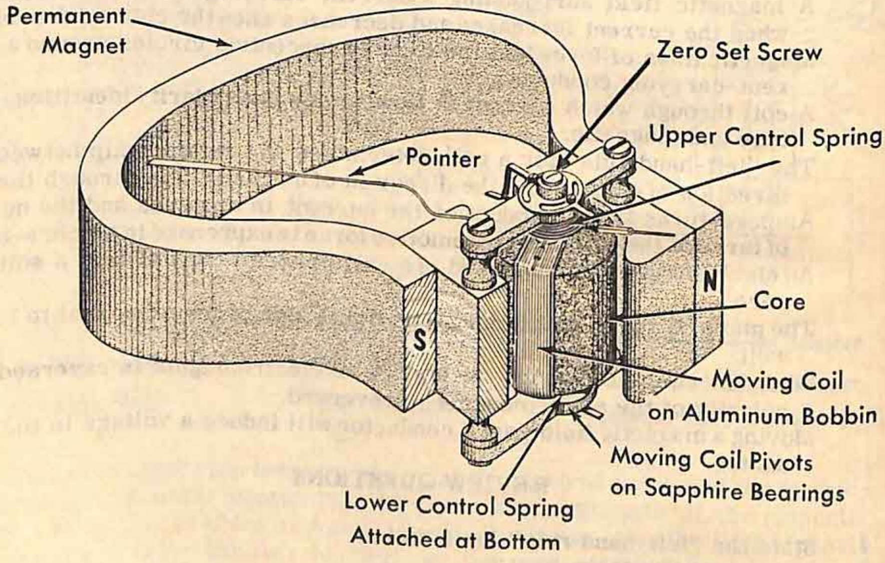
REVIEW QUESTIONS

1. State the "left-hand rule" for a coil.
2. What is an electromagnet?
3. What forms do the magnetic lines of force take around a current-carrying conductor?
4. What is the practical unit of magnetomotive force?
5. How does an increase or decrease in current through a conductor affect its magnetic field?
6. How do the magnetic fields of an electromagnet and a permanent magnet differ?
7. Define reluctance. Define permeability.
8. Give two methods for making artificial magnets.
9. How does a permanent magnet differ from a temporary magnet?
10. What is the maxwell? What is 1 maxwell equal to?
11. What happens in a conductor when a magnetic field is moved past it?

Electrical Measuring Devices: The D'Arsonval Meter

Electrical measuring instruments are used for checking the operation of electrical and radio equipment. The most commonly-measured electrical quantities are current, voltage, and resistance. The basic instrument used in d-c ammeters, voltmeters, and ohmmeters is the D'Arsonval permanent magnet, moving-coil d-c meter. Its principle of operation is like that of the d-c motor. Because the torque or rotational force developed in the d-c moving coil is directly proportional to the current flowing through the coil, the scale gradations of d-c current meters are uniformly divided (linear).

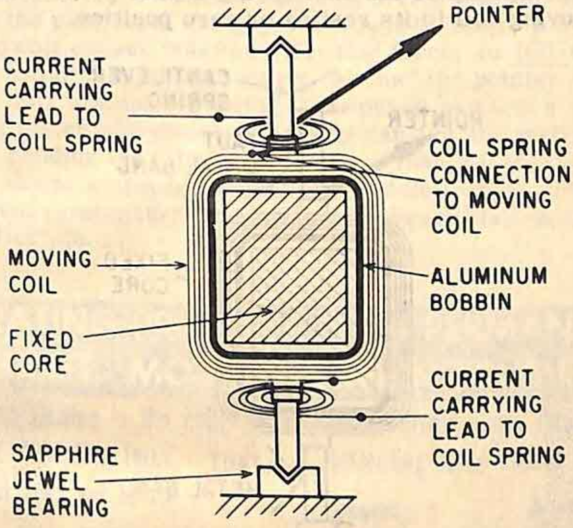
COMPONENT PARTS OF THE BASIC D'ARSONVAL PERMANENT-MAGNET MOVING-COIL INSTRUMENT


Permanent Magnet
Zero Set Screw
Upper Control Spring
Pointer
N
Core
S
Moving Coil on Aluminum Bobbin
Moving Coil Pivots on Sapphire Bearings
Lower Control Spring Attached at Bottom

As shown in the illustration of the motor movement on the following page, a current-carrying loop (the moving coil) is wound on an aluminum frame or bobbin mounted around a circular core of magnetic material. The entire coil assembly is positioned between the pole pieces of a permanent horseshoe magnet. The mounting pins of the assembly pivot on sapphire (jewel) bearings. A top and bottom spring, mechanically attached to the coil assembly, conduct the meter current to and from the coil; spring load the coil to prevent free spinning when magnetic reactions develop the turning force; and supply the restoring forces which return the coil to its normal position when meter current ceases flowing. A pointer attached to the coil swings across the meter scale as the coil turns between the pole pieces. Currents induced in the aluminum bobbin "damp" the moving coil and prevent it from moving back and forth around the point of deflection.

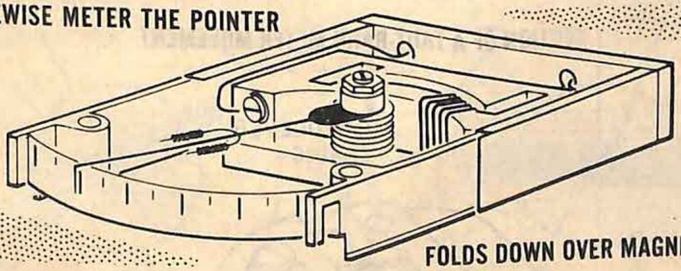
D'Arsonval Meter (Cont'd)

When space is at a premium, an edgewise D'Arsonval meter movement can be used. In this type of meter, the pointer folds down over the edge of the magnet and the scale, resulting in a very "flat" meter. In fact, as many as three meters can sometimes be mounted in roughly the same panel area as that required for a single conventional square meter.

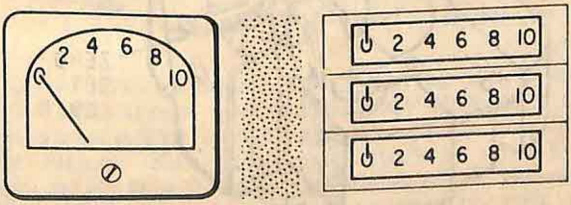

POINTER
CURRENT CARRYING LEAD TO COIL SPRING
COIL SPRING CONNECTION TO MOVING COIL
MOVING COIL
ALUMINUM BOBBIN
FIXED CORE
CURRENT CARRYING LEAD TO COIL SPRING
SAPPHIRE JEWEL BEARING

SECTION OF A JEWELED METER MOVEMENT

IN AN EDGEWISE METER THE POINTER



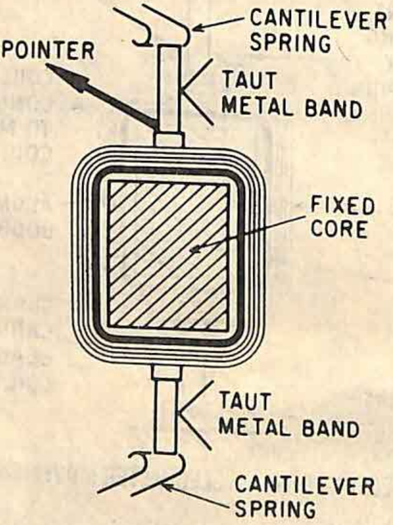
FOLDS DOWN OVER MAGNET AND SCALE



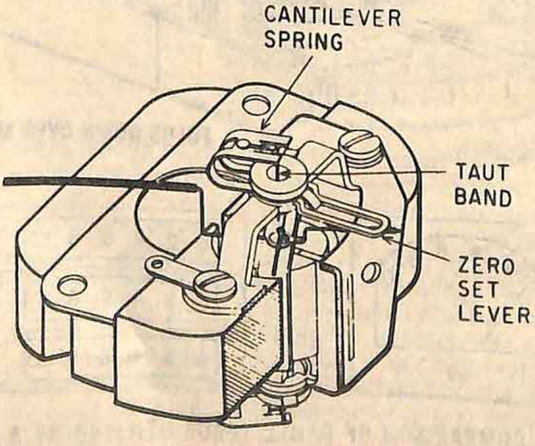
A COMPARISON OF PANEL SPACE UTILIZED BY A SINGLE SQUARE METER AND THREE EDGEWISE METERS

Taut-Band Meter

A newer development in D'Arsonval meter design is a taut-band movement. Its operation is identical to that of the D'Arsonval movement previously described. However, the coil springs are replaced by flat taut bands made of metal. The taut bands are held between cantilever springs that keep the bands taut. The cantilever springs and the taut bands act as conductors to the moving coil. The flat taut bands act as a spring-load to prevent free spinning and to return the moving coil to its resting or zero position.



SECTION OF A TAUT-BAND METER MOVEMENT

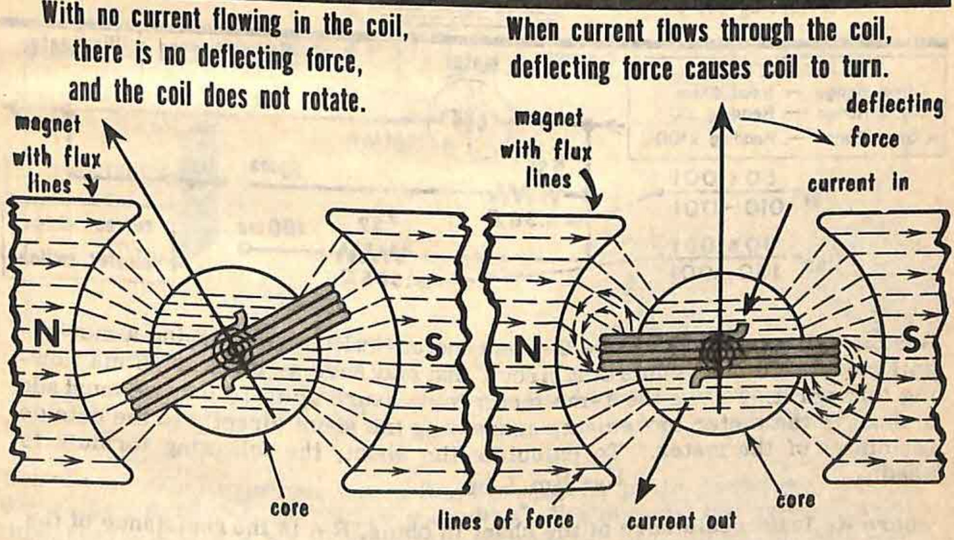


CONSTRUCTION OF A TAUT-BAND METER MOVEMENT

Operation of the Moving-Coil D-C Meter as a Current Meter

Although the moving-coil d-c meter is used to measure voltage and resistance, as well as current, it is basically a current-operated device. The current in the moving coil develops the magnetic field that reacts with the stationary magnetic field of the permanent magnet (produces rotary motion of the coil) and moves the meter pointer across the scale of the instrument. The direction of rotation of the coil is from the strengthened portion to the weakened portion of the resultant magnetic field, just as in the d-c motor. Depending on the particular design of a current meter, a certain maximum current in the coil causes maximum turning force, or full-scale deflection. Exceeding the maximum current rating "slams" the pointer off scale against the end stop. For example, passing 2 amperes through a 0.5 ampere (500 milliamperes) meter movement can easily damage the meter by burning out the coil or by bending the thin pointer. Less than full-scale current flowing in the coil produces a proportionately reduced deflection. Thus, 50 milliamperes of current flowing through a 100-milliamperes full-scale meter causes half-scale deflection.

OPERATING PRINCIPLE OF A PERMANENT MAGNET, MOVING-COIL INSTRUMENT

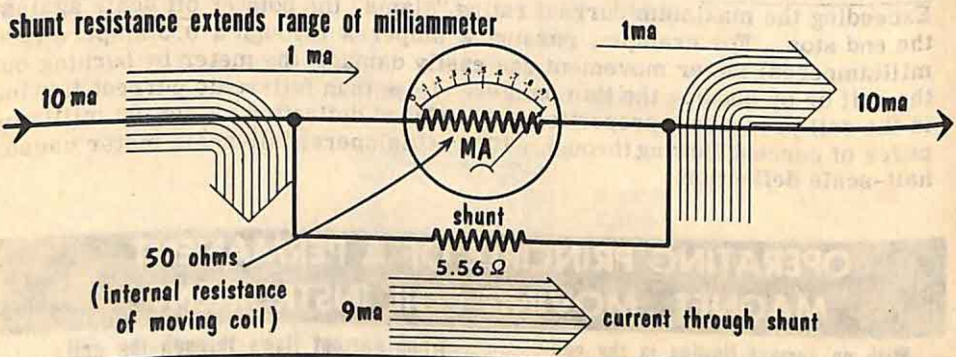

With no current flowing in the coil, there is no deflecting force, and the coil does not rotate.

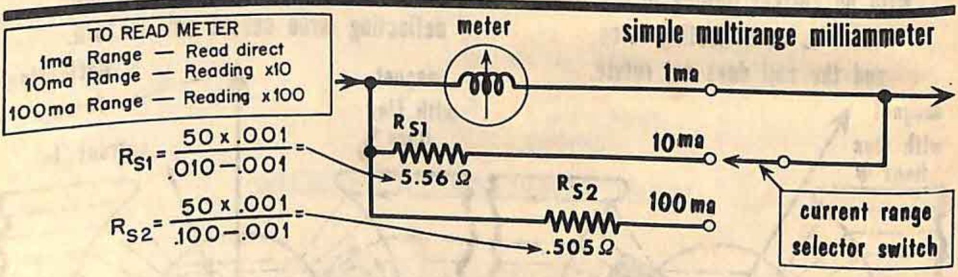
When current flows through the coil, deflecting force causes coil to turn.

Some current meter designs incorporate a moving coil in which as little as 10 microamperes of current causes full-scale deflection; other coils may require 50 microamperes of current and still others may be designed for 1 milliampere or higher. How can these meters be used to measure more current than can safely flow through the moving coil? The problem is solved by using a parallel current path, or shunt, around the coil, either inside or outside the meter. This arrangement is explained on the next page.

How to Calculate the Resistance of a Shunt

Although it is not conventional practice for users of radio test equipment to build shunts for current meters, it is still valuable to know how the resistance of a meter shunt is calculated. The general philosophy of the meter shunt is as follows: if a meter is designed to indicate the flow of 1 milliampere (ma) of current at full-scale deflection and it is desired to measure 10 ma, the ohmic value of the shunt must be such(relative to the ohmic value of the moving coil in the meter) that 9/10 of the total current (9 ma) passes through the shunt and 1/10 of the current (1 ma) passes through the meter.


shunt resistance extends range of milliammeter
1 ma
1ma
10 ma
10ma
MA
shunt
5.56 Ω
50 ohms
(internal resistance of moving coil)
9ma
current through shunt


TO READ METER
1ma Range — Read direct
10ma Range — Reading x10
100ma Range — Reading x100
meter
simple multirange milliammeter
1ma
10ma
100ma
$R_{S1} = \frac{50 \times .001}{.010 - .001} =$
$R_{S2} = \frac{50 \times .001}{.100 - .001} =$
R S1
5.56 Ω
R S2
.505 Ω
current range selector switch

Assume that we wish to use a 0-1-ma meter (milliameter) having a moving-coil resistance of 50 ohms in a circuit that may have as much as 10 ma flowing through it. To use the 1-ma meter to measure up to 10 ma, we must add a shunt to the meter movement, connecting the shunt directly to the outside terminals of the meter. To calculate the shunt, the following formula is used:

$$R_S = \frac{R_m \times I_m}{I_t - I_m}$$

where R_S is the resistance of the shunt in ohms, R_m is the resistance of the meter movement in ohms, I_m is the full-scale current rating of the meter movement, and I_t is the total current in amperes to be carried by the meter and shunt. Substituting the values, we get:

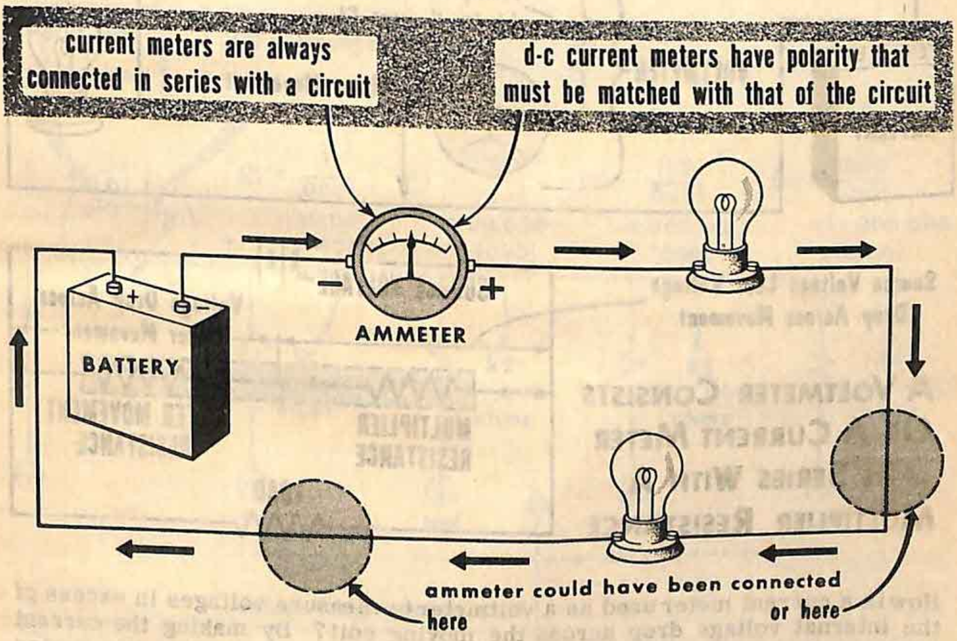
$$R_S = \frac{50 \times .001}{.010 - .001} = \frac{.05}{.009} = 5.56 \text{ ohms}$$

The construction of accurate shunts can be done using precise resistance-measuring devices. To calculate other shunts, substitute the new values in the above formula.

Using the Current Meter

Reference to d-c current meters includes ammeters, milliammeters, and microammeters. Meters suitable for measuring full-scale currents up to 500 microamperes (μa) are considered to be microammeters; from 500 μa (0.5 ma) up to 500 ma full scale are milliammeters; and from 500 ma (0.5 ampere) or more full scale are ammeters.

The first rule for proper use of current meters is that they must be connected in series with the circuit where the current is to be measured. The current must flow through the meter. Usually, this means "breaking" into the circuit to insert the instrument. However, some circuits provide jacks for insertion of current meters where measurements are to be made. As a safety precaution, always disconnect the voltage source when inserting a current meter into the circuit.

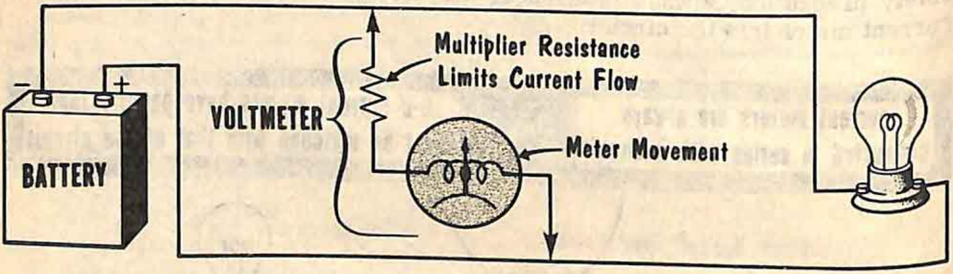

current meters are always connected in series with a circuit
d-c current meters have polarity that must be matched with that of the circuit
AMMETER
−
+
BATTERY
+
−
ammeter could have been connected
here
or here

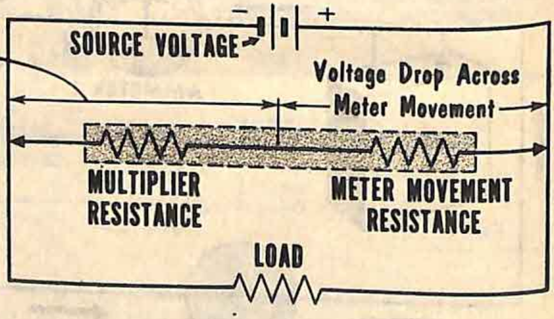
The second rule for proper use is that the polarity of the meter be correct. Using the polarity of the voltage source as a reference, the current must flow into the meter at its negative terminal and out of the meter at its positive terminal. If the polarity is wrong, the meter pointer will move in the opposite direction and possibly damage the meter.

The third rule is that whenever uncertain as to how much current is in a circuit, always start at the highest current range of a meter. If the pointer barely moves away from the zero point, turn the meter range switch to the next lower current range. Continue doing this until there is sufficient deflection to obtain an accurate reading.

The D-C Moving-Coil Voltmeter

The d-c moving-coil current meter is the basis of the d-c moving-coil voltmeter. A d-c current meter can be used as a d-c voltmeter in the following way: Assume that a current meter has a moving coil rated at 100 μa (.0001 ampere) full-scale current and a d-c resistance of 1000 ohms. Full-scale coil current means, therefore, a voltage drop ($E = IR$) of $.0001 \times 1000 = 0.1$ volt across the moving coil of this instrument. In fact, every current meter bears a fixed, internal voltage-drop rating equal to the product of the full-scale coil current and the d-c resistance of the coil. Thus, although the ability to measure voltage is inherent in every current meter, its usefulness is limited because its maximum range and resistance are both very low.



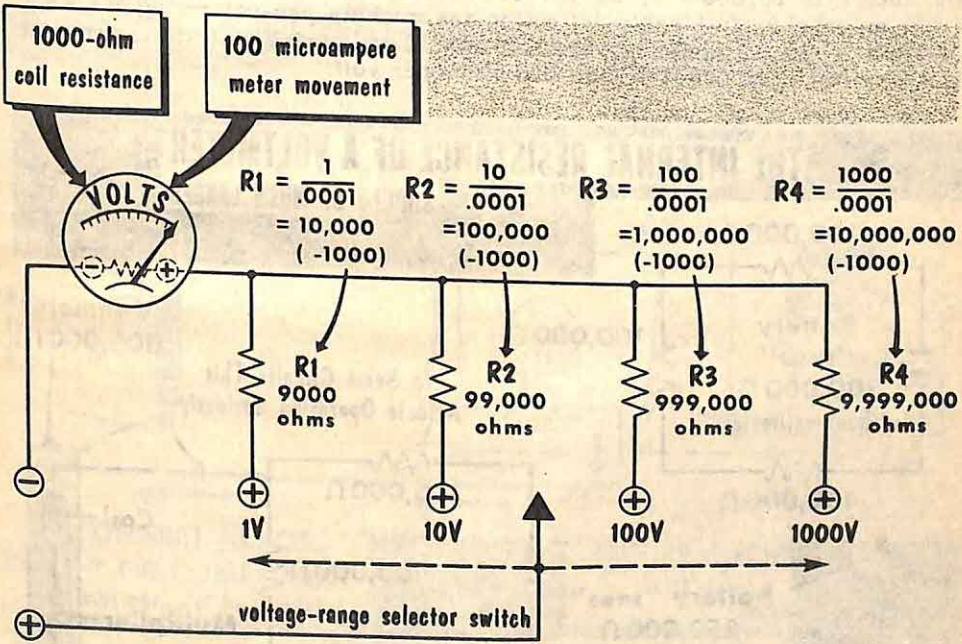

Source Voltage Less Voltage Drop Across Movement
–
+
SOURCE VOLTAGE
Voltage Drop Across Meter Movement
MULTIPLIER RESISTANCE
METER MOVEMENT RESISTANCE
LOAD

A VOLTMETER CONSISTS OF A CURRENT METER IN SERIES WITH A MULTIPLIER RESISTANCE

How is a current meter used as a voltmeter to measure voltages in excess of the internal voltage drop across the moving coil? By making the current meter part of a circuit in which a multiplier resistance is placed in series with the meter coil. The ohmic value of the multiplier resistance is such that when added to the meter coil resistance, the total resistance limits the circuit current to the full-scale current rating of the meter for any given applied voltage. In this way, the applied voltage divides between the multiplier resistance and the meter resistance in direct proportion to their respective resistances; the voltage drop across the meter coil never exceeds the internal voltage rating for full-scale deflection. The function of the multiplier resistance is to develop a voltage drop equal to the excess between the applied voltage (the voltage being measured) and the internal voltage drop across the meter coil. This proportioning of voltage drops becomes automatic when the multiplier resistance limits the circuit current as described.

Calculating the Multiplier

Let us assume that we have a 100-microampere ammeter (microammeter) having a d-c resistance of 1000 ohms. We want to convert this meter movement into a voltmeter that reads 25 volts full scale. When the 100-μa full-scale current flows through the meter, there is a voltage drop of 0.1 volt across the meter coil. Our task then is to calculate what resistance must be placed in series with the meter movement so that when a current of 100 microamperes flows through the meter and resistance, there will be a 25-volt drop across the meter resistance and multiplier combination. We can find the total resistance of the combination at 25 volts by using Ohm's law ($R = E/I = 25/.0001$, or 250,000 ohms). Of course, we must not lose sight of the internal meter resistance of 1000 ohms. Thus, the series multiplier resistance is equal to 250,000 ohms less the meter resistance of 1000 ohms, or 249,000 ohms.


1000-ohm coil resistance
100 microampere meter movement
VOLTS
R1 = 1/.0001 = 10,000 (-1000)
R2 = 10/.0001 =100,000 (-1000)
R3 = 100/.0001 =1,000,000 (-1000)
R4 = 1000/.0001 =10,000,000 (-1000)
R1 9000 ohms
R2 99,000 ohms
R3 999,000 ohms
R4 9,999,000 ohms
1V
10V
100V
1000V
voltage-range selector switch

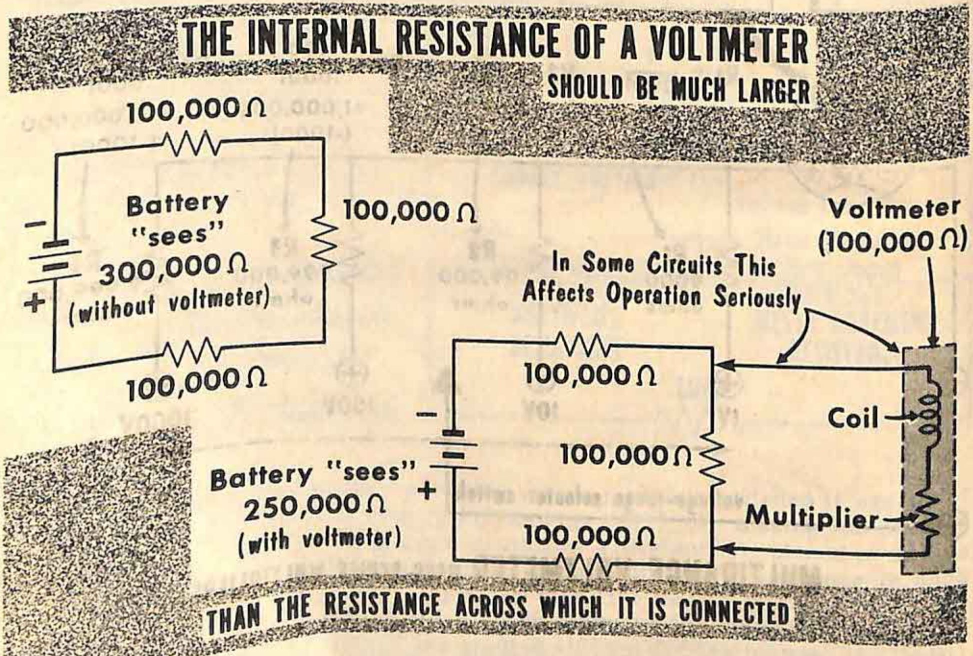
MULTIRANGE VOLTMETER USES SERIES MULTIPLIERS

By using a number of multiplier resistances that can be connected in series with the meter coil by a selector switch, a series of voltage ranges can be provided. Each range is suitable for measuring all d-c voltages between zero and the maximum value. As we will see, any current meter can be converted into a voltmeter by suitable selection of a series multiplier; however, the most desirable current meters are those having high sensitivity (1 ma or less for full-scale deflection).

D-C Voltmeters—Ohms-Per-Volt Rating

An important electrical characteristic of voltmeters is their ohms-per-volt rating. This term is the basis for the total resistance of the voltmeter on each of its voltage ranges (including the multiplier resistance used on each range). The ohms-per-volt rating is based on the current requirement of the meter coil for full-scale deflection. If the meter coil in a voltmeter requires 50 μa (.00005 ampere) for full-scale deflection, the multiplier resistance required for each volt indication is $R = E/I$, or $1/.00005 = 20,000$ ohms. The instrument therefore has a rating of 20,000 ohms-per-volt on each range.

The total resistance of the instrument on each range, then, is the ohms-per-volt rating multiplied by the full-scale limit on each range. For example, if the range selected is 5 volts full scale, the total resistance presented by the meter is 20,000 × 5, or 100,000 ohms. A meter that requires 1 ma (.001 ampere) for full-scale deflection has an ohms-per-volt rating of 1/.001 or 1000. If the voltmeter movement uses a 10-μa moving coil, the instrument has a rating of 1/.00001 or 100,000 ohms per volt.


THE INTERNAL RESISTANCE OF A VOLTMETER
SHOULD BE MUCH LARGER
100,000 Ω
Battery "sees" 300,000 Ω (without voltmeter)
100,000 Ω
100,000 Ω
Voltmeter (100,000 Ω)
In Some Circuits This Affects Operation Seriously
100,000 Ω
Coil
100,000 Ω
Battery "sees" 250,000 Ω (with voltmeter)
Multiplier
100,000 Ω
THAN THE RESISTANCE ACROSS WHICH IT IS CONNECTED

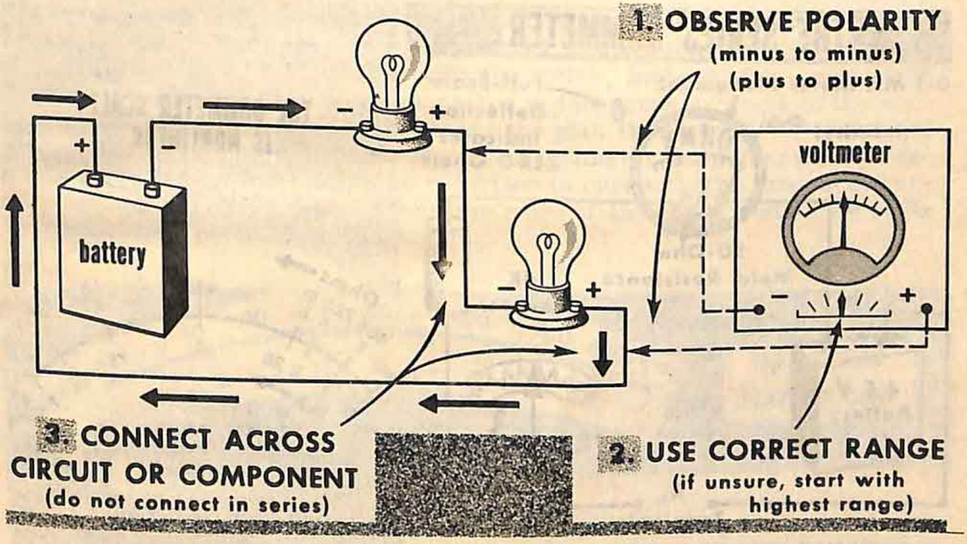
Voltmeters are connected across circuits; hence, the resistance of the voltmeter is in parallel with the resistance of the circuit being measured. To minimize the shunting effect of the voltmeter resistance across the circuit resistance, it is essential that the voltmeter resistance be as high as possible. It is therefore best to use the highest range possible consistent with readability.

Using the Voltmeter Properly

There are three general rules to keep in mind when using the voltmeter. The first rule concerns polarity. The d-c moving coil movement must be connected so that current flows through the coil in the proper direction. If current passes in the reverse direction, the pointer will deflect backwards and the meter possibly will be damaged. All d-c meters have positive and negative terminals, and connection to a circuit should be made in accordance with the polarities of the voltages or voltage drops being measured.

The second rule deals with the selection of the correct voltage range. If the approximate voltage is known, use a range that allows a safe tolerance. If the voltage to be measured is unknown and unpredictable, start with the highest range the voltmeter permits. Then, move to lower ranges until one is reached that permits an accurate reading.

USE THE VOLTMETER PROPERLY

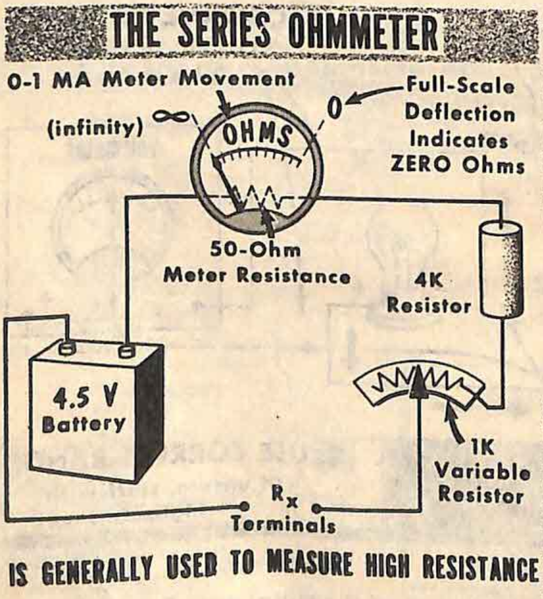

1. OBSERVE POLARITY
(minus to minus)
(plus to plus)
voltmeter
battery
+
−
−
+
−
+
−
+
3. CONNECT ACROSS CIRCUIT OR COMPONENT
(do not connect in series)
2. USE CORRECT RANGE
(if unsure, start with highest range)

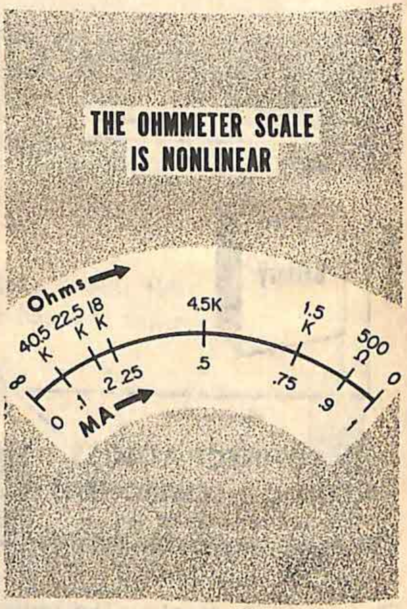
The third rule involves the actual connection of the voltmeter. Since a voltmeter is a comparatively high-resistance instrument, it is always connected across, or in parallel, with the load or voltage source. Since the voltmeter shunts the component which it measures, the voltmeter resistance should be as high as possible so as not to affect circuit operation. The highest range that provides a reliable reading should always be used. On a 20,000-ohms-per-volt meter, a 10-volt range presents a resistance of 200,000 ohms. If the actual reading is about 8 or 9 volts, then the 50-volt range, which presents a shunt resistance of 1 megohm, can be used. This would not affect the operation of a circuit unless its resistance was in excess of 100K ohms.

The Series Ohmmeter

The same moving-coil meter that we used in our ammeter and voltmeter can be used to make an ohmmeter, an instrument for measuring resistance. In building a basic ohmmeter circuit, we start once again with a 0-1 ma meter movement connected in series with a fixed resistor (4K), a variable resistor (1K), and a 4.5-volt battery (see illustration). This entire circuit ends in a pair of terminals across which the unknown resistance (R_X) is to be placed.

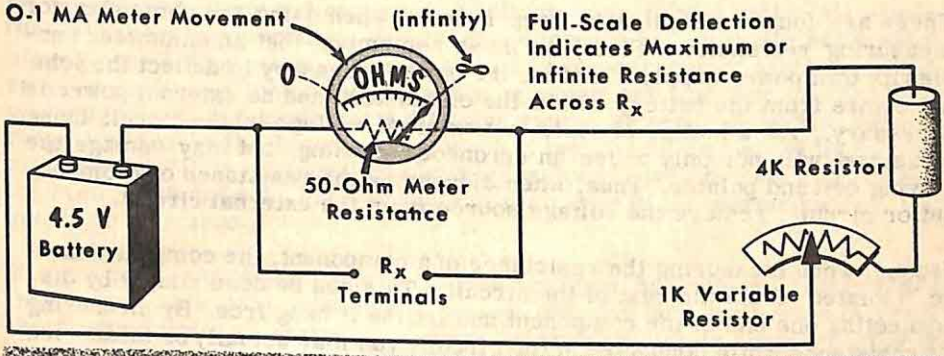
When the unknown or external resistance is zero, or the output terminals are short circuited, we want enough current to flow for full-scale meter deflection. By Ohm's law, 1 ma will flow when the total series circuit resistance is: $R = 4.5/.001$, or 4500 ohms. Since it is possible for the voltage of a new battery to be slightly higher than 4.5 volts, the total series resistance should be about 5000 ohms to be safe. Having a fixed resistance of 4000 ohms and a variable resistance of 1000 ohms permits "zero-adjust" to be made on the ohmmeter. As the battery voltage lowers with age, the potentiometer is varied to give full-scale deflection when R_X is zero.





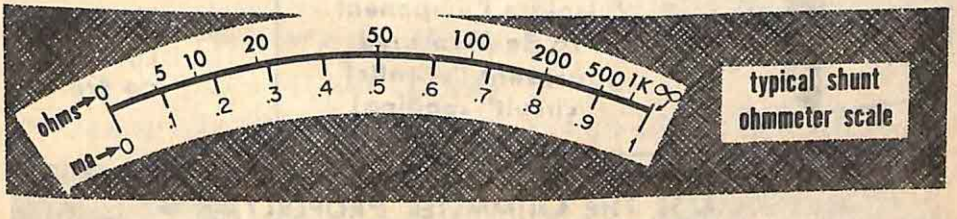
From this, we see that in the series ohmmeter, full-scale deflection is equal to zero ohms at the input terminals. With R_X "open," this is equivalent to an infinitely-high resistance. Thus, the left side of the meter scale reads "infinity," or some very high value of resistance. We see then that the ohmmeter scale reads opposite in direction to the ammeter and voltmeter scales. In addition, it is not a linear scale. If R_X is 1500 ohms, circuit current drops .25 ma, to .75 ma ($I = 4.5/6000$). However, the addition of another 1500 ohms across R_X produces a current of $I = 4.5/7500$, or .60 ma, a drop of an additional .15 ma. This produces the nonlinear scale shown.

The Shunt Ohmmeter



THE SHUNT OHMMETER is used generally to measure low resistance

For reading very low values of resistance, the shunt-type ohmmeter is better suited than the series type. In the shunt unit, the unknown resistance R_X is now shunted or placed in parallel with the meter, instead of in series with it. With the unknown resistance connected in this manner, some of the current in the ohmmeter circuit now takes the path through R_X. The current through the meter movement is reduced accordingly, and the amount of deflection drops in proportion to the reduction in current. The amount of current through the meter depends upon the ratio of the shunt resistance of R_X to the internal resistance of the meter.



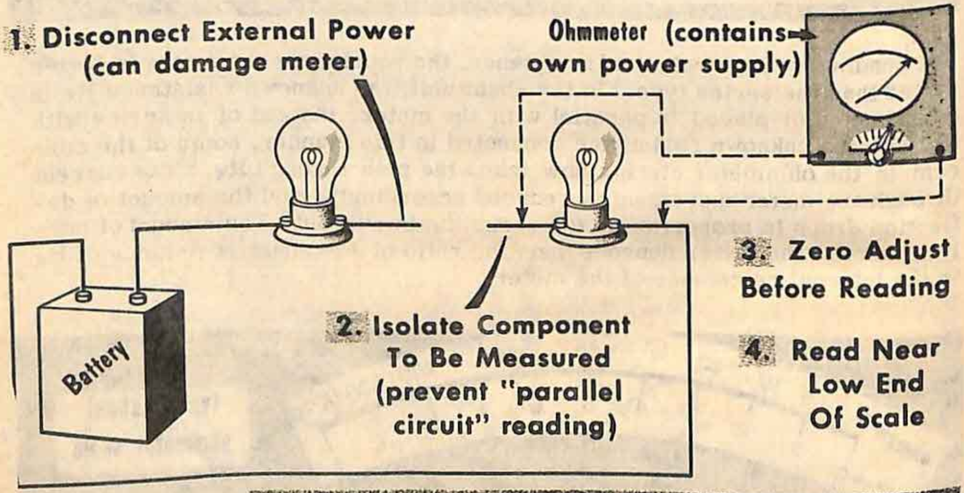
typical shunt ohmmeter scale

The zero-adjust in the shunt ohmmeter operates oppositely from that in the series ohmmeter. In the shunt instrument, the variable resistor is adjusted so that full-scale current flows through the moving coil when there is an open circuit across the R_x terminals. Thus, maximum or infinite resistance is indicated on the right-hand side of the meter scale. A short circuit across terminals R_x would bypass all current around the meter and produce no pointer deflection. Thus, zero ohms would appear at the left-hand side of the meter scale. Any resistance connected across the R_x terminals will provide a path for current, and will cause the current through the meter to be less than full scale. Low resistances will bypass considerable current and produce little deflection; high resistances will bypass little current and produce large deflection. By using a selector switch and various-sized shunts, a multirange ohmmeter can be made, with each range having a different multiplying factor.

Using the Ohmmeter

There are four basic rules to keep in mind when using the ohmmeter for measuring resistance. First, we must remember that an ohmmeter carries its own power supply. That is, the power necessary to deflect the pointer comes from the battery within the ohmmeter, and no external power is necessary. As a matter of fact, any external voltage in the circuit being measured will not only cause an erroneous reading, but may damage the moving coil and pointer. Thus, when measuring the resistance of a component or circuit, remove the voltage source from the external circuit.

Second, when measuring the resistance of a component, the component must be "isolated" from the rest of the circuit. This can be done simply by disconnecting one end of the component and letting it hang free. By measuring its resistance while connected in the circuit, you may actually be measuring the combined resistance of the component and that of some shunt component.


1. Disconnect External Power (can damage meter)
Ohmmeter (contains own power supply)
Battery
2. Isolate Component To Be Measured (prevent "parallel circuit" reading)
3. Zero Adjust Before Reading
4. Read Near Low End Of Scale

USE THE OHMMETER PROPERLY

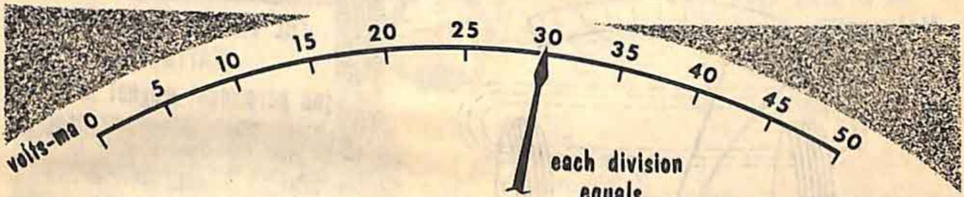
Third, make the zero adjustment before making a reading. If the ohmmeter is not properly adjusted to read zero ohms accurately, all other readings made will be incorrect.

Fourth, always make a resistance reading near the low end of the resistance range. At this point, the resistance values on the meter scale are spread out and a more accurate reading can be made. Avoid reading at the high end; here, the resistance values are crowded and the slightest inaccuracy of the ohmmeter can cause a considerable error in a resistance reading. If a particular resistance reads near the high end of a resistance range, switch to the next higher range; this will cause the pointer to indicate at a much lower place on the meter scale.

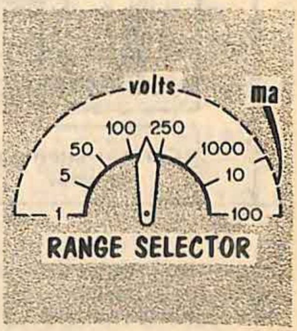
D-C Meter Scales

Meter scales used for d-c current and voltage meters have uniformly-spaced (linear) calibration markings. Single-range meters have a single scale showing only one set of values. This is so either for current or voltage. Multirange meters may have a single scale on which several sets of values are marked, with each set serving a different range, or separate scales for each range covered by the instrument. When a meter is designed to be used for many ranges, it is equipped with a range-selector switch. Each position on the switch indicates the highest value of the range of measurement. All ranges begin with zero.

The d-c meter used for resistance measurement has non-uniformly spaced (nonlinear) calibration markings. Although only one set of numerals is associated with a scale, a resistance range-selector switch is always part of the instrument. Each switch position bears a multiplying factor; i. e., X1, X10, X100, etc. The proper reading on that particular range is equal to the meter scale reading multiplied by the multiplying factor on the range switch.



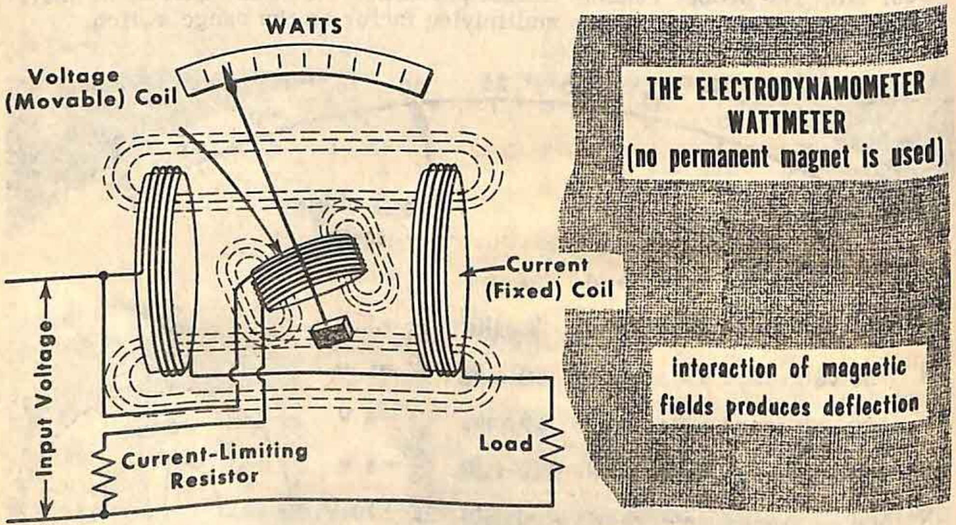
			each division equals
ON	1-volt range meter reads	.6 volt	$\frac{1}{50}$ = .02 V
ON	5-volt range meter reads	3 volts	$\frac{5}{50}$ = .1 V
ON	50-volt range meter reads	30 volts	$\frac{50}{50}$ = 1 V
ON	100-volt range meter reads	60 volts	$\frac{100}{50}$ = 2 V
ON	250-volt range meter reads	150 volts	$\frac{250}{50}$ = 5 V
ON	1000-volt range meter reads	600 volts	$\frac{1000}{50}$ = 20 V
ON	10-ma range meter reads	6 ma	$\frac{10}{50}$ = .2 ma
ON	100-ma range meter reads	60 ma	$\frac{100}{50}$ = 2 ma



The amount of change between any two adjacent divisions on any one range is equal to the maximum value of the range divided by the number of divisions. If a voltmeter scale consists of 50 divisions and full-scale deflection is 250 volts, each division then corresponds to 250/50 or 5 volts. If this same meter were indicating 25 ma full scale, each division would be equal to 25/50 or 0. 5 ma. If the scale consisted of 100 divisions, each division would represent 2. 5 volts or 0. 25 ma. Occasionally, the pointer comes to rest between scale markings. In this case, the user must determine the value of the scale markings on either side of the pointer, and then estimate the approximate value of the reading.

The Wattmeter

We have discussed thus far the various ways and means of measuring voltage, current, and resistance. Another important measurement is that of power. Since power is equal to the product of voltage and current (E × I), we can obtain this measurement by voltmeter and ammeter readings in a circuit. There is, however, a direct means for measuring power in watts--the electrodynamometer wattmeter. This wattmeter consists of two coils--one stationary and one movable. There are two ways of connecting a wattmeter. In one method, the stationary coil is the voltage coil and consists of many turns of small wire having a high resistance; the movable coil is the current coil and consists of a few turns of large wire having low resistance. The voltage (or high-resistance) coil is connected across the voltage source, or across the device whose power consumption is being measured. The current (or low-resistance) coil is connected in series with the load, and current through the load passes through the current coil.



THE ELECTRODYNAMOMETER WATTMETER (no permanent magnet is used)

interaction of magnetic fields produces deflection

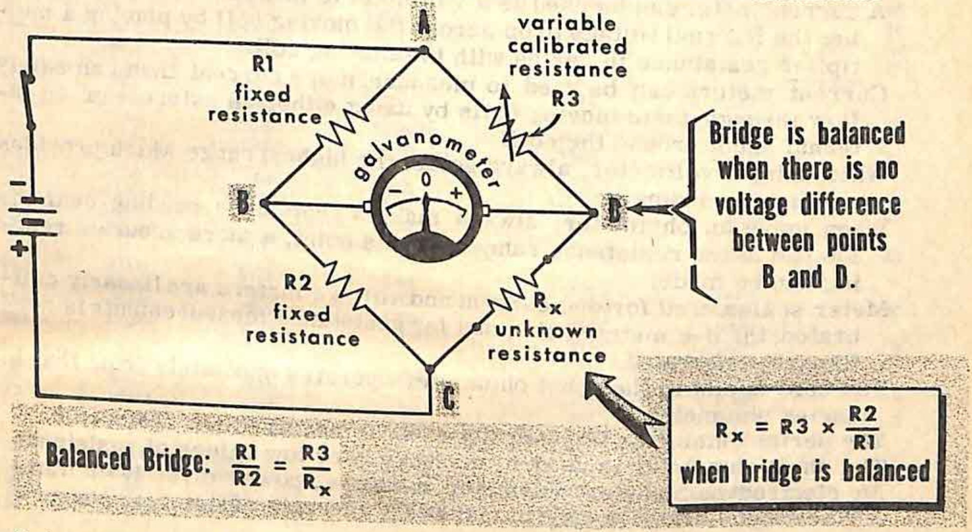
The second method of wattmeter connection has the high-resistance voltage coil as the movable coil, with the low-resistance current coil being stationary. This second method is superior for large currents because it removes the difficulty in conducting large currents into and out of the spring suspension of the moving coil.

Current through the voltage coil is proportional to the voltage across the load. The interaction of the magnetic fields from the fixed and movable coils causes the movable coil to rotate. The effect is almost the same as if the voltage applied across the load and the current through the load were multiplied together. The torque on the movable coil is proportional to the current and also to the voltage; it is therefore proportional to their product. The meter pointer thus registers according to the power consumption E × I. As we will learn later, wattmeters are used more in a-c circuits than in d-c circuits.

The Wheatstone Bridge

It is often necessary to make resistance measurements of greater accuracy than is possible with an ohmmeter. Measuring ammeter shunts, voltmeter multipliers, and other high-precision resistances can be done with an instrument known as the Wheatstone bridge. In the schematic of the bridge, resistances R1 and R2 are fixed and form one leg of the bridge. The other leg of the bridge consists of variable resistance R3 and the unknown resistance R_X. The applied battery voltage appears across both branches of this parallel circuit and produces current flow.

WHEATSTONE BRIDGE PROVIDES HIGH-ACCURACY RESISTANCE MEASUREMENTS



Bridge is balanced when there is no voltage difference between points B and D.

Balanced Bridge: $\frac{R1}{R2} = \frac{R3}{R_x}$

$R_x = R3 \times \frac{R2}{R1}$ when bridge is balanced

Let us assume that the battery voltage is 10 volts, R1 = 1 ohm, and R2 = 9 ohms. The current through the A-B-C leg would be 1 ampere, with point B being 1 volt positive with respect to point A. In leg A-D-C there will also be current flow. Let us assume the unknown resistance is 90 ohms, and the variable resistance is adjusted to 10 ohms. The current flow in this leg would then be 0.1 ampere or 100 ma (I = 10/100). The 0.1 ampere flowing through R3 would cause a voltage drop of 1 volt, with a 9-volt drop across R_X. Thus, point D would also be 1 volt positive with respect to point A. Since points B and D are both 1 volt positive with respect to point A, they are at the same potential, and no current will flow through the galvanometer. However, should the ratio of R1 to R2 differ from that of R3 to R_X, points B and D would not be at the same potential, and current would flow from B to D or D to B, depending on which point was at the higher potential.

R3 is usually a calibrated resistor which is varied until the galvanometer reads zero, indicative of no difference of potential across it. It is important to remember that R1 and R2 need have only a known ratio. Commercial bridges often have plug-in units or means of changing the R1-R2 ratio in terms of 1:1, 10:1, 100:1, 1000:1, etc.

SUMMARY

The basic d-c meter is the permanent-magnet, moving-coil type called the D'Arsonval movement.

The moving coil d-c meter is used to measure voltage, current, and resistance.

Voltmeters are always connected across a circuit being measured; ammeters are always connected in series with a circuit being measured.

D-c current meters include ammeters, milliammeters, and microammeters.

Correct polarity must be observed when measuring current to avoid damaging the meter.

Always begin at the highest range of a current meter whenever in doubt as to how much current is in a circuit.

A current meter can be used as a voltmeter to measure voltages exceeding the internal voltage drop across the moving coil by placing a multiplier resistance in series with the moving coil.

Current meters can be used to measure more current than can safely flow through their moving coils by using either an external or an internal shunt around the coil.

When using a voltmeter, always select the highest range which provides a reliable reading.

When using an ohmmeter, always make a resistance reading near the low end of the resistance range. At this point, a more accurate reading can be made.

Meter scales used for d-c current and voltage meters are linearly calibrated; the d-c meter scale used for resistance measurements is nonlinearly calibrated.

The zero adjust in the shunt ohmmeter operates oppositely from that in series ohmmeter.

The series ohmmeter is generally used to measure high resistance.

The shunt ohmmeter is used to measure very low values of resistance.

An electrodynamometer wattmeter measures power directly in watts.

A Wheatstone bridge is used to make very accurate resistance measurements.

REVIEW QUESTIONS

1. Why must the power be disconnected when an ohmmeter is placed in the circuit?
2. What is the basic meter movement used in d-c ammeters, voltmeters, and ohmmeters?
3. When is a meter shunt resistance used?
4. What formula is used to calculate the resistance of a meter shunt?
5. How should current meters be connected in a circuit where current is to be measured?
6. How is a current meter used as a voltmeter to measure voltage greater than the internal voltage drop across the moving coil?
7. What is meant by the ohms-per-volt rating of a meter?
8. How are voltmeters connected in a circuit?
9. What three rules should be remembered for correct use of a voltmeter?
10. How do series ohmmeters and shunt ohmmeters differ?
11. What type of wattmeter directly measures power in watts?
12. When is a Wheatstone bridge used?

AMERICAN WIRE GAGE TABLE (B & S)

FOR STANDARD ANNEALED BARE COPPER WIRE (at 68°F)

Gage	Diameter (inches)	Area (circ. mils)	Weight (lbs. per 1000 ft.)	Resistance (ft. per ohm)	Resistance (ohms per 1000 ft.)	Current Capac (amps-rubber in
0000	.4600	211600.	640.5	20400.	.04901	225
000	.4096	167800.	507.9	16180.	.06180	175
00	.3648	133100.	402.8	12830.	.07793	150
0	.3249	105500.	319.5	10180.	.09827	125
1	.2893	83690.	253.3	8070.	.1239	100
2	.2576	66370.	200.9	6400.	.1563	90
3	.2294	52640.	159.3	5075.	.1970	80
4	.2043	41740.	126.4	4025.	.2485	70
5	.1819	33100.	100.2	3192.	.3133	55
6	.1620	26250.	79.46	2531.	.3951	50
7	.1443	20820.	63.02	2007.	.4982	
8	.1285	16510.	49.98	1592.	.6282	35
9	.1144	13090.	39.63	1262.	.7921	
10	.1019	10380.	31.43	1001.	.9989	25
11	.09074	8234.	24.92	794.	1.260	
12	.08081	6530.	19.77	629.6	1.588	20
13	.07196	5178.	15.68	499.3	2.003	
14	.06408	4107.	12.43	396.0	2.525	15
15	.05707	3257.	9.858	314.0	3.184	
16	.05082	2583.	7.818	249.0	4.016	6
17	.04526	2048.	6.200	197.5	5.064	
18	.04030	1624.	4.917	156.5	6.385	3
19	.03589	1288.	3.899	124.2	8.051	
20	.03196	1022.	3.092	98.5	10.15	
21	.02846	810.1	2.452	78.11	12.80	
22	.02535	642.4	1.945	61.95	16.14	
23	.02257	509.5	1.542	49.13	20.36	
24	.02010	404.0	1.223	38.96	25.67	
25	.01790	320.4	.9699	30.90	32.37	
26	.01594	254.1	.7692	24.50	40.81	
27	.01420	201.5	.6100	19.43	51.47	
28	.01264	159.8	.4837	15.41	64.90	
29	.01126	126.7	.3836	12.22	81.83	
30	.01003	100.5	.3042	9.691	103.2	
31	.008928	79.7	.2413	7.685	130.1	
32	.007950	63.21	.1913	6.095	164.1	
33	.007080	50.13	.1517	4.833	206.9	
34	.006305	39.75	.1203	3.833	260.9	
35	.005615	31.52	.09542	3.040	329.0	
36	.005000	25.00	.07568	2.411	414.8	
37	.004453	19.83	.06001	1.912	523.1	
38	.003965	15.72	.04759	1.516	659.6	
39	.003531	12.47	.03774	1.202	831.8	
40	.003145	9.888	.02993	0.9534	1049.	
41	.00280	7.8400	.02373	.7559	1323.	
42	.00249	6.2001	.01877	.5977	1673.	
43	.00222	4.9284	.01492	.4753	2104.	
44	.00197	3.8809	.01175	.3743	2672.	
45	.00176	3.0976	.00938	.2987	3348.	
46	.00157	2.4649	.00746	.2377	4207.	

GLOSSARY

Alnico Magnet—Permanent magnet consisting of aluminum, nickel, and cobalt.

Ampere-Hour—Unit of electricity equal to a current of one ampere flowing for a period of one hour.

Ampere-Turns—Product of the number of turns in a coil times the current in amperes flowing through the coil.

Atom—The smallest particle into which matter can be divided.

Ballast Resistor—Resistor whose resistance increases rapidly with increases in current flow through it.

Battery—Device for converting chemical energy into electrical energy.

Charged Bodies—Bodies with an excess or a deficiency of electrons.

Coulomb—The unit of quantity for electric current.

D'Arsonval Meter Movement—Most commonly used movement in precision instruments for making d-c measurements.

Difference of Potential—Voltage between two points.

Direct Current—Unidirectional electric current flowing in one direction through a circuit, and essentially constant in magnitude.

Discharge—In a storage battery, conversion of chemical energy into electrical energy.

Electrolyte—Chemical compound, either liquid or pastelike, whose chemical action causes a current flow, or in which a chemical action is caused by the flow of current.

Electromagnet—Core of magnetic material (such as soft iron) which becomes temporarily magnetized by an electric current passed through a coil of wire wound around the core.

Electromotive Force (emf)—Force which tends to alter the motion of electricity or to maintain its motion against resistance. Measured in volts.

Electron—Elementary negative charge that revolves around the nucleus of an atom; negatively-charged particles of matter.

Flux—Term used to designate all the magnetic lines of force in a region.

Flux Density—Number of magnetic lines of force passing through a given area.

Free Electrons—Electrons which are not bound to a particular atom but wander at random among the many atoms of a substance.

Fuse—Protective device used in an electric circuit containing a wire, bar, or strip of fusible metal. Wire melts and breaks when current through it exceeds the rated value of the fuse.

Induced Voltage—Voltage produced by a change in the number of magnetic lines of force passing through a coil in a circuit.

Insulator—Device having high electric resistance used for separating conductors to prevent undesired flow of current from the conductors to other objects.

Ion—Electrified particle which is formed when an atom or group of atoms loses or gains one or more electrons.

IR drop—Voltage drop produced across a resistance R by the flow of current I through the resistance.

I^2R Loss—Power loss in connecting wires and other parts of a circuit caused by current flow I through resistance R of the conductors.

Junction—Connection point between two or more conductors.

Kilowatt—Unit of electrical power equal to 1000 watts.

Law of Magnetism—Like poles repel; unlike poles attract.

Load—Device used to absorb power and convert it into a desired useful form.

Lodestone—A kind of iron ore (magnetite) which is a natural magnet.

Magnetic Flux—Lines of force generated by a magnet.

Magnetic Lines of Force—Imaginary lines used to designate the direction in which magnetic forces are acting as a result of a magnetomotive force.

Molecule—Smallest subdivision of a compound which still retains the chemical properties of that compound.

Ohm—Unit of electrical resistance.

Ohm's Law—Expresses the relationship existing in an electrical circuit between the voltage E, the current I, and the resistance R. $E = IR$; $I = E/R$; $R = E/I$.

Parallel Circuit—Two or more electrical devices connected so the line current divides between them.

Permeability—Measure of how much better than air a given material is as a path for magnetic lines of force.

Polarity—Condition in an electrical circuit whereby the direction of current flow can be determined.

Potential—Difference in voltage between two points of a circuit. Expressed in volts.

Potentiometer—A variable voltage divider.

Power—Rate of doing work or expending energy. In d-c circuits, multiplying volts by amperes gives power in watts. $P = EI$; $P = I^2R$; $P = E^2/R$.

Primary Cell—Cell designed to produce an electric current through electrochemical reaction. Cannot be recharged by electric current when completely discharged.

Proton—Positive particle in an atom. Smallest quantity of positive electricity that can exist in a free state.

Reluctance—Property of a magnetic circuit which determines the amount of magnetic flux that will be produced as a result of applying a given magnetomotive force.

Resistance—Opposition which a device or material offers to the flow of current.

Rheostat—Resistor whose value can be varied. Used to handle large currents.

Secondary Cell—Source of electrical energy where the cell may be recharged after being discharged by sending an electric current through it opposite in direction to the discharge current.

Series Circuit—Two or more electrical devices connected so that the total current must flow through each of them in turn.

Shunt—Any part, or component, connected in parallel with some other part, or component.

Solenoid—Electromagnet having an energizing coil, cylindrical or tubular in form, acting on an armature positioned in the center of a coil. A coil used to produce a magnetic field.

Static Charge—Electric charge accumulated on an object.

Thermistor—Temperature-sensitive resistor whose resistance changes negatively as its temperature increases.

Variable Resistor—Resistor whose value can be changed mechanically.

Varistor—Voltage-sensitive resistor whose resistance changes as the voltage applied to it changes. Its resistance lowers when a high voltage is present.

Volt—Unit of electromotive force or electrical pressure.

Voltage Drop—A difference, or loss of voltage, between two points.

Watt—Practical unit of electrical power.

Watthour Meter—Meter that registers and measures electrical energy in watthours or kilowatthours.

Wheatstone Bridge—Null-type resistance-measuring circuit in which resistance is measured by direct comparision with a standard resistance.

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BASIC RADIO

REVISED EDITION

VOLUME 1

MARVIN TEPPER

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